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RESULTS OF FATIGUE TESTS OF BARE AF1410 STEEL UNNOTCHED FLAT PLATES WITH SURFACE CORROSION DAMAGE

by

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8 May 2008

DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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The global maritime operating environment of U.S. Naval Aviation assets necessitates their prolonged exposure to severe corrosive environments. The resulting corrosion damage on flight critical structural components has a significant adverse impact on fleet readiness and total ownership costs. To address these issues, NAVAIR has initiated a multi-year research program to investigate and quantify the fatigue life reduction due to corrosion on high-strength steels, and to develop models and metrics to implement actionable maintenance criteria for corrosion damage. In order to develop models that can quantify the severity of corrosion damage with respect to a reduction in fatigue life, a robust set of well-characterized test results on representative test specimens is required. This report documents the results of a set of tests to quantify the fatigue life of bare AF1410 steel unnotched flat plates with various stages of laboratory-induced corrosion damage on the surface. The test data set includes a detailed characterization of the topology of surface corrosion damage on all test specimens, allowing a quantitative assessment of corrosion severity to be performed, given that an appropriate model is developed.

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SUMMARY

The global maritime operating environment of U.S. Naval Aviation assets necessitates their prolonged exposure to severe corrosive environments. The resulting corrosion damage on flight critical structural components has a significant adverse impact on fleet readiness and total ownership costs. Much of the costs and inconvenience of corrosion damage repair can be traced to uncertainty over the severity of corrosion necessary to cause a significant reduction in the fatigue life of a damaged component. This uncertainty has resulted in qualitative maintenance criteria for corrosion damage repair that are difficult to implement in practice, and do not provide objective measures of the reliability and risk associated with continued flight operation. To address these issues, NAVAIR has initiated a multi-year research program to investigate and quantify the fatigue life reduction due to corrosion on high-strength steels, and to develop models and metrics to implement actionable maintenance criteria for corrosion damage.

To develop models that can quantify the severity of corrosion damage with respect to a reduction in fatigue life, a robust set of well-characterized test results on representative test specimens is required. The purpose of this report is to document the results of a set of tests to quantify the fatigue life of bare AF1410 steel unnotched flat plates with various stages of corrosion damage on the surface. The corrosion on the test plates was induced in a laboratory environment, and the corrosion process was neutralized prior to fatigue testing in laboratory air. The topology of the corrosion damaged surfaces was fully characterized on each specimen prior to testing.

All of the plates that failed during testing cracked inside the gage area of the specimen. The uncorroded plates all had critical cracks that initiated from small gouge marks on the specimen surfaces, most likely from the longitudinal grinding operation during specimen manufacture. A few of the corroded plates that were tested cracked outside the corrosion patch. For these plates, the surface defects on the uncorroded portion of the plates had a high enough stress concentration to override the local stress concentrations due to the corrosion. For the corroded specimens that cracked in the corrosion patch, all of the cracks initiated from small semi-elliptical notches that formed as a result of the corrosion process. The corrosion characteristic data and fatigue test results documented in this report can provide an excellent foundation for the development of metrics to characterize the severity of corrosion damage with respect to fatigue life reduction, and probabilistic models to predict the fatigue life reduction of corrosion-damaged airframe components.

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INTRODUCTION

BACKGROUND

The global maritime operating environment of U.S. Naval Aviation assets necessitates their prolonged exposure to severe corrosive environments. The resulting corrosion damage on flight critical structural components has a significant adverse impact on fleet readiness and total ownership costs. Much of the costs and inconvenience of corrosion damage repair can be traced to uncertainty over the severity of corrosion necessary to cause a significant reduction in the fatigue life of a damaged component. This uncertainty has resulted in qualitative maintenance criteria for corrosion damage repair that are difficult to implement in practice, and do not provide objective measures of the reliability and risk associated with continued flight operation. To address these issues, NAVAIR has initiated a multi-year research program to investigate and quantify the fatigue life reduction due to corrosion on high-strength steels, and to develop models and metrics to implement actionable maintenance criteria for corrosion damage.

PREVIOUSLY PUBLISHED REPORTS

A compendium of the tasks and technical accomplishments of the NAVAIR corrosion-fatigue research program that are completed to date is in the report “Navy High-Strength Steel Corrosion-Fatigue Modeling Program,” (reference 1) for the period ending October 2006.

PURPOSE

To develop models that can quantify the severity of corrosion damage with respect to a reduction in fatigue life, a robust set of well-characterized test results on representative test specimens is required. The purpose of this report is to document the results of a set of tests to quantify the fatigue life of bare AF1410 steel unnotched flat plates with various stages of corrosion damage on the surface. The corrosion on the test plates was induced in a laboratory environment, and the corrosion process was neutralized prior to fatigue testing in laboratory air. The topology of the corrosion damaged surfaces was fully characterized on each specimen prior to testing. A previous set of test specimens similar to those discussed here has also been tested, and is documented in reference 1. Those tests are referred to in the documentation as “Batch A” results. The set of tests discussed in this document were completed after the Batch A tests, and are referred to as “Batch B” results. The corrosion characteristic data and fatigue test results will be used to develop probabilistic models to predict the fatigue life reduction of corrosion-damaged airframe components, and metrics to characterize the severity of corrosion damage with respect to fatigue life reduction.

METHODS

TEST SPECIMEN MANUFACTURE

The AF1410 high strength steel material referred to as “Batch B” came from a single forged billet that was approximately 8 in. square by 94 in. long. The material was purchased from Ellwood National Forge Co., and was manufactured by Carpenter Technology Co. As-received, the material was certified to have the chemical composition listed in table 1, and to be in the normalized and overaged condition.

Table 1: Chemical Composition of AF1410 Billet Used to Manufacture Batch B Specimens

C	MN	SI	S	P	S&P	CR	NI	MO	CO
0.152	0.04	0.04	0.003	0.006	0.009	2.00	10.04	1.01	14.04
TI	O	N	AL						
0.012	0.0012	<0.001	0.011						

Tensile test coupons were also machined from the Batch B billet prior to heat treatment to serve as travelers for heat treatment process verification. The coupons were 0.25 in. diameter and 1.0 in. long in the gage section, with 3/8-16 threaded grip ends, and were cut from the billet in the longitudinal direction. Compact tension C(T) coupons were machined for fracture toughness and crack growth rate tests of the AF1410 Batch B material. Rough specimen blanks were cut from the billet while in the normalized and overaged condition, in the L-T orientation. The blanks were then heat treated prior to final machining by Hercules Heat Treating Corporation per Boeing PS-15167H process specification, except that no grit blast was performed. Final machining to nominal dimensions was performed by the University of Dayton Research Institute (UDRI). Fracture toughness coupons had a width of 2.0 in. and thickness of 1.0 in. in accordance with ASTM E399 (reference 2). Crack growth coupons had a width of 2.50 in. and thickness of 0.30 in., with the other dimensions as specified by ASTM E647 (reference 3).

A total of 72 corrosion-fatigue plate specimens was manufactured from the Batch B billet. Rough specimen blanks of 17 in. x 2.5 in. x 0.75 in. were cut from the billet by UDRI using the cut-up diagram shown in figure 1. Rough blanks were heat treated by Hercules Heat Treating Corporation to the Boeing PS-15167H proces spec, except that no grib blast was performed after heat treating.

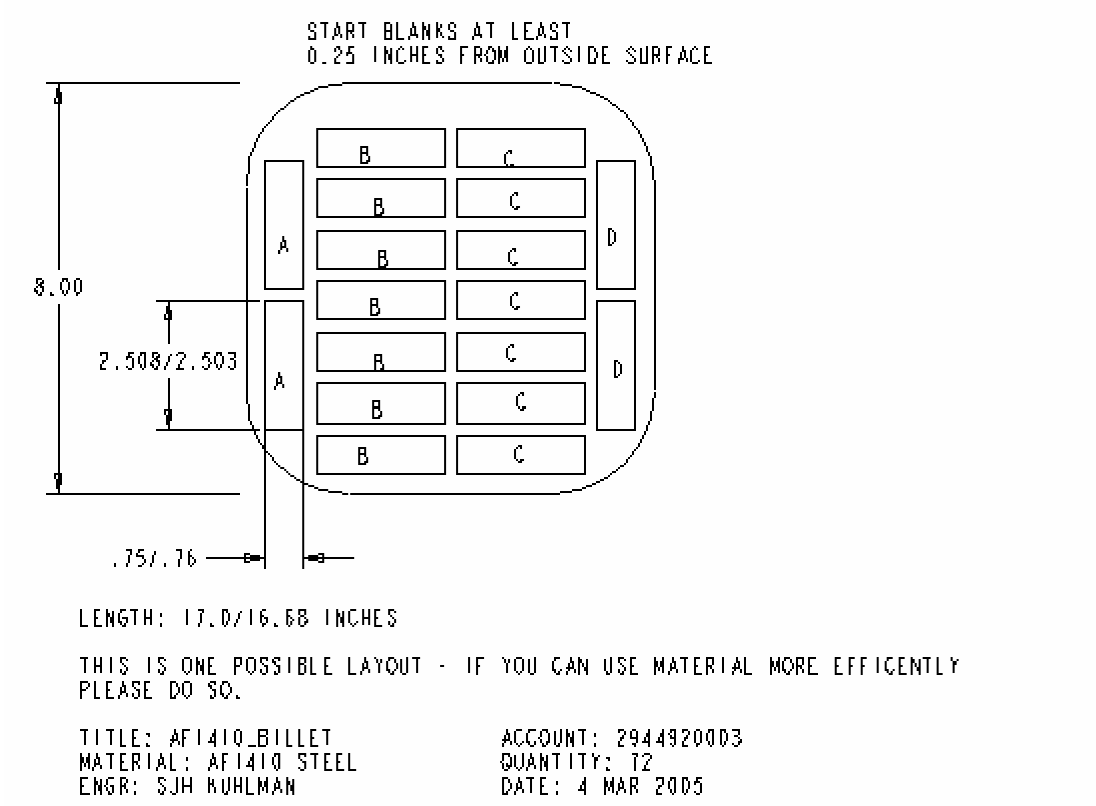

Figure 1: Billet Cut-up Diagram for AF1410 Batch B C-F Specimens

Specimen blanks were machined to the final dimensions shown in the drawing in appendix A, following heat treatment. This specimen geometry was chosen to minimize the geometric stress concentration in the transition region between the gage and grip sections. The maximum stress concentration (K_t) on the test specimen gage surface is 1.033. A contour plot of the axial stress distribution in the test plate is shown in figure 2, for a net section stress of 200 ksi.

After initial trials using different machining methods, it was determined that grinding the corrosion-fatigue specimens from the rectangular, heat treated, blanks to the final dimensions was the preferred method. Ultimately, UDRI worked with a local grinding finisher, Accu-Grind and Manufacturing Company, to develop procedures to manufacture the specified radii in the specimen contour and at the edge corners of the test plate specimens.

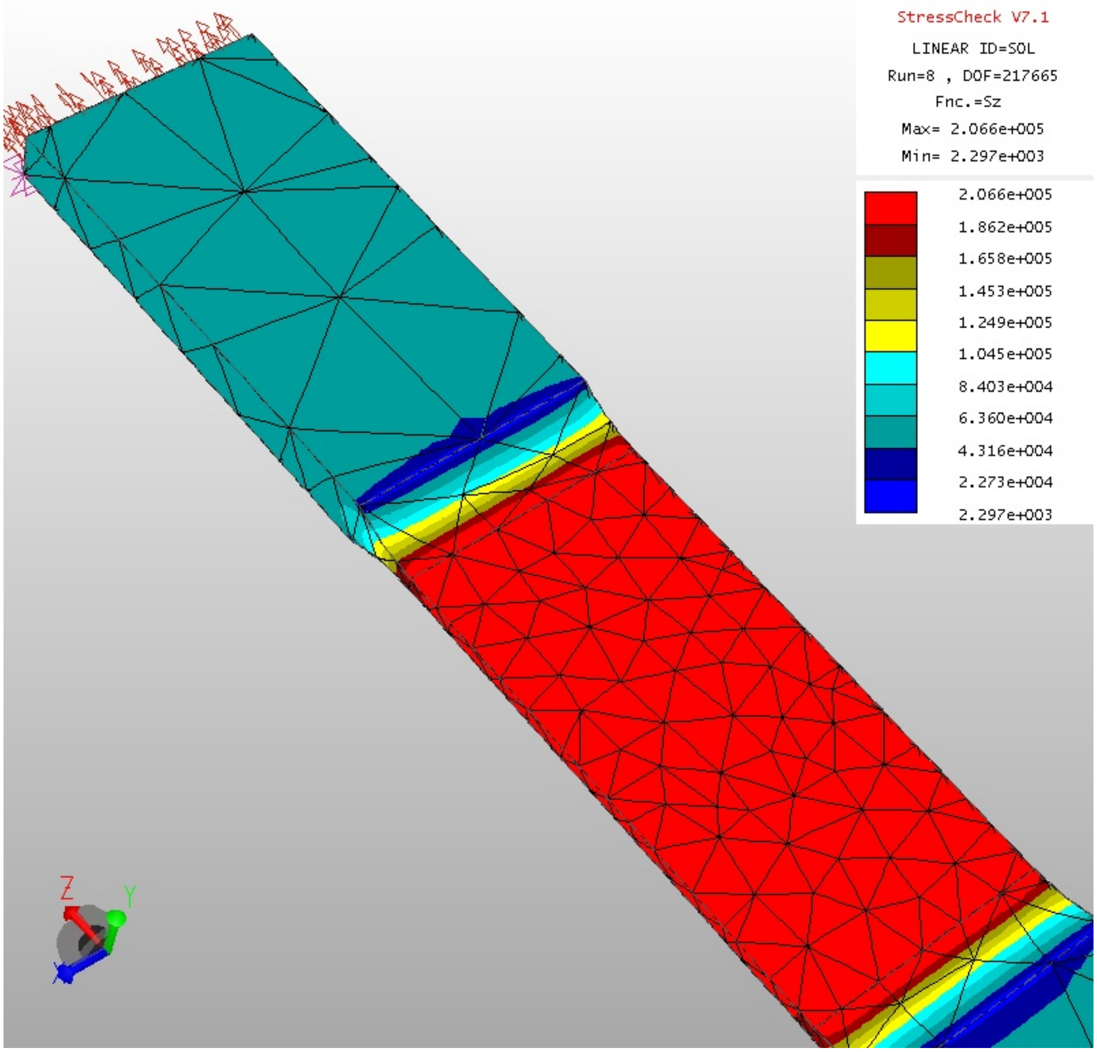

Figure 2: Axial Stress Contour Plot of AF1410 Batch B Corrosion-Fatigue Test Specimen, 200 ksi Net Section Stress

TEST PLATE SURFACE PREPARATION

Different methods of final grinding were explored in order to reduce the residual stresses imparted on the surfaces due to specimen manufacture. Similarly, different methods of surface preparation were studied in order to achieve an appropriate surface finish required for baseline fatigue testing (i.e., with no corrosion exposure). Ultimately, the procedures employed for the Batch B test plate specimens included low-stress grinding techniques in the final machining steps and hand polishing. The resulting surface finish was substantially different from the grit blasted surface finish of the Batch A test plate specimens.

UDRI worked with the same grinding finisher that manufactured the corrosion-fatigue specimens to develop the low-stress grinding procedures for the final machining steps of the test plate specimens. Grinding materials, material removal rate, grinding speeds, and coolant were selected and applied to minimize residual stresses in the material.

Hand polishing was performed in the gage section and radii of each specimen after final low-stress grinding. The surfaces addressed by the hand polishing included the plate surfaces, the edge surfaces, and the corners between the tab ends. The operator polished the surfaces by running dry, backed, SiC or Al2O3 abrasive paper on the specified surfaces in the specimens' loading direction by hand. The finalized hand polishing procedures called for the use of 180, 240, 320, and 400 grit SiC or Al2O3 paper on each surface in order to achieve the appropriate surface finish, free of machine grinding flaws due to drag. Detailed procedures regarding hand polishing the corrosion-fatigue specimens are explained in appendix B.

Surface residual stress measurements were performed on several test specimens after manufacture, but prior to corroding in order to quantify the amount of residual stress induced in the specimens by the manufacturing process (tables 2 and 3). Subsurface residual stress measurements were also performed on three specimens and surface measurements on seven specimens. Lambda Research, Inc., performed the residual stress measurements. Sectioning was necessary prior to x-ray diffraction residual stress measurement in order to facilitate fixturing for the subsurface measurements. Any stress relaxation caused by sectioning was assumed to be negligible. X-ray diffraction residual stress measurements were made at the surface and at nominal depths of 0.5, 1.0, 2.0, and 3.0 x 10-3 in. (13, 25, 51, and 76 x 10-3 mm). Measurements were made in the longitudinal direction at the center of the low stress grind (LSG) side. The longitudinal residual stress distribution measured as a function of depth and surface residual stress are plotted in figures 3 and 4 with the raw data listed in appendix C.

Table 2: Processing Techniques and Residual Stress Measurements for Batch B C-F Specimens

MANUFACTURE PROCESS	FINISHING PROCESS	RS Surface Only Multiple Locations	RS 1 Surface + Depth DESTRUCTIVE
1 - Specimens saw processes prior to being received by AccuGrind	**1A** Aggressive Hand Polishing All Surfaces and Edges	545-1 (already have pre-hand polish RS measurement. Testable) ALL OTHER SPECIMENS MECHANICALLY TESTED	547-18C (already have pre-hand polish RS measurement. Too thin to mechanically test) ALL OTHER SPECIMENS MECHANICALLY TESTED
	1B Machine Polishing All Surfaces (heat may have been high), Hand Polishing Edges 400 grit only (minimal hand polishing on surfaces - 400 grit, when required)	All Specimens Mechanically Tested to Failure - (I,0hr), (II,0hr), (III,6hr), (IV,6hr) NONE AVAILABLE	
2 - Accugrind received blanks	**2C** Machine Polishing All Surfaces (heat may have been high), newly received have not done any additional polishing	614-23 (In-house, Testable)	614-20 (In-house, Testable)
	2D Machine Polishing using Low Heat Accumulation Techniques and then Aggressive Hand Polishing 180 to 400 grit on all surfaces and edges	614-9 (In-house, Testable)	614-26 (In-house, NOT Testable)
3 - Specimens made from CF Tabs	**3E** Aggressive Hand Polishing All Surfaces and Edges	598-11, 598-14, 598-15 (In-house, Testable) Extra three specimens (15 required, 18 made, Still testable)	NONE

1A =	29 out of 60 specimens	48.33 %
1B =	13 out of 60 specimens	21.67 %
2C =	0 out of 60 specimens	0.00 %
2D =	18 out of 60 specimens	30.00 %
3E =	N/A	

Table 3: Batch B C-F Specimen Residual Stress Measurements

LSG Specimen #	UDRI Process Type	Type Residual Stress	No. of Measurements	Comments
545-1	1A	Surface	2	Surface measurements only
614-23	2C	Surface	2	Surface measurements only
614-9	2D	Surface	2	Surface measurements only
547-40B	1A	Surface	1	Surface measurements only
598-11	3E	Surface	1	Gage Section- 2" long; Surface measurement only
598-14	3E	Surface	1	Gage Section- 2" long; Surface measurement only
598-15	3E	Surface	1	Gage Section- 2" long; Surface measurement only
547-18C	1A	Surface & Depth Profile	1	Measure depth near center of gage section
614-20	2C	Surface & Depth Profile	1	Measure depth near center of gage section
614-26	2D	Surface & Depth Profile	1	Measure depth near center of gage section

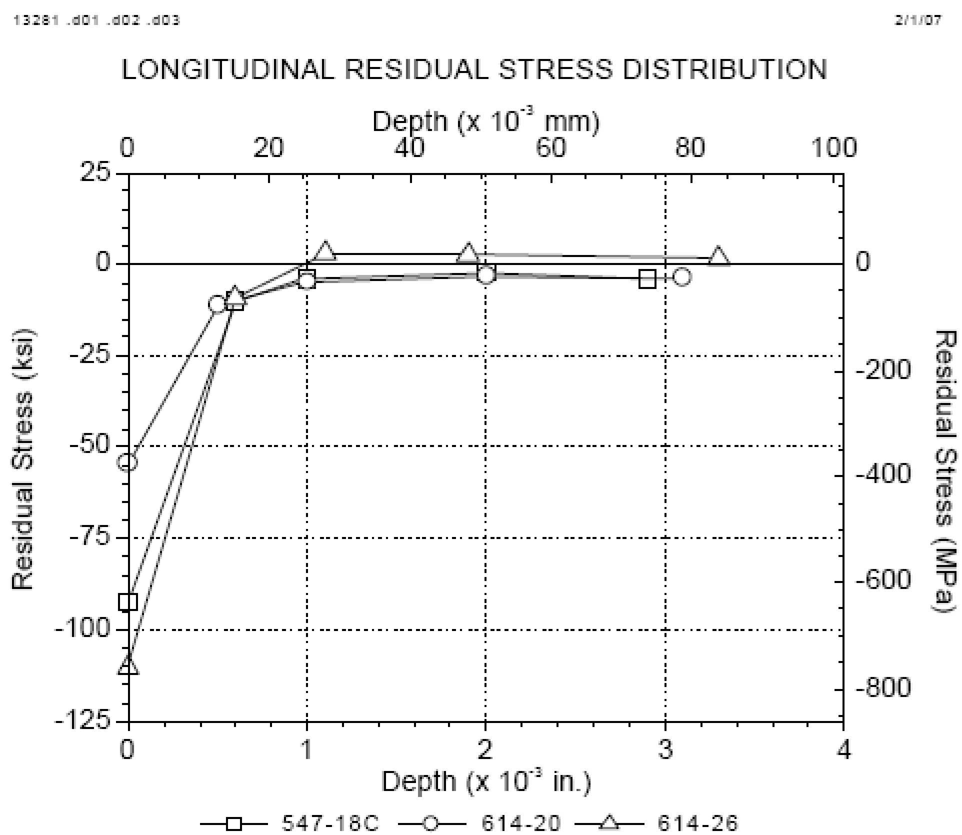

Figure 3: Longitudinal Residual Stress Depth Measurements, AF1410 Batch B Plates

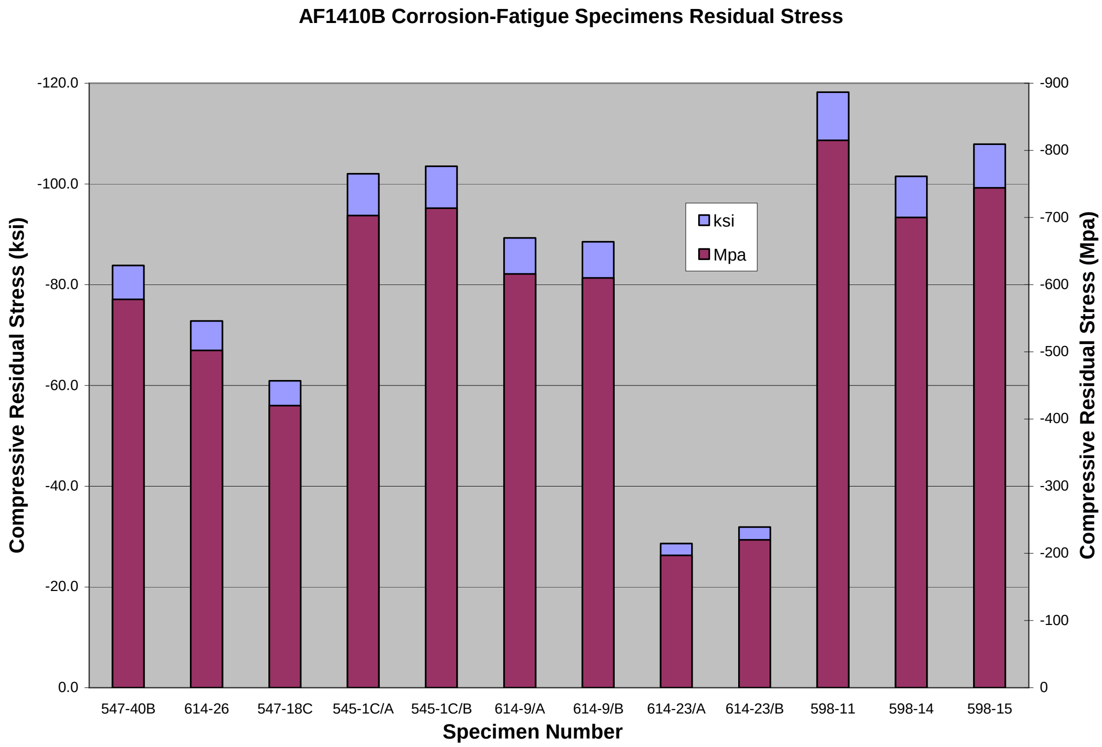

Figure 4: Surface Residual Stress Measurements, AF1410 Batch B Plates

TEST PLATE CORROSION PROCEDURES

The corrosion exposure of each Batch B fatigue test plate specimen was performed by UDRI using the same method employed for the Batch A specimens. The method uses filter paper soaked in salt solution applied to the test plate in the desired location. A voltage is then applied across the specimen and an electrode to bias the direction of the current and accelerate the electrochemical corrosion process. The technique was developed by UDRI on this Program for AF1410 high strength steel to eliminate the issues identified while studying standard methods. Namely to eliminate the need for specimen masking, which causes corrosion to undercut at the masked edges; and to eliminate the need for long exposure times, which can be days, weeks, or months. A description of the corrosion exposure testing and selection process for use on this program can be found in reference 1.

The UDRI exposure method uses filter paper soaked in a solution containing 3.5% NaCl, in order to deliver it directly to the center of the test plate gage section without the need to mask off surrounding areas. Circular pieces of filter paper with sizes varying between 0.875 in. and 1.0625 in. in diameter were used on the Batch B specimens in order to corrode an area just over 1 in. in diameter in the gage section center of each test plate. That corrosion patch size provides for a statistically significant number of corrosion features without being too large that the post

inspections were too time consuming. The circular shape of the filter paper minimizes the potential for stress risers that a square shape may impose at the corrosion patch interfaces.

A voltage is applied across the specimen with the soaked filter paper and an electrode in place to accelerate the corrosion process. A flat AF1410 wafer acts as an electrode, which is placed on top of the filter paper (the wafer is larger than the filter paper). A voltage source is connected to the electrode and to the specimen with the proper polarity to bias the direction of the reaction. Resistors in the circuitry and the voltages used were chosen according to the desired current density of ~ 12.75 $mA/in.^2$ (2 mA/cm^2), which was determined through initial testing. See figure 5 for a diagram of the electrochemical cell setup.

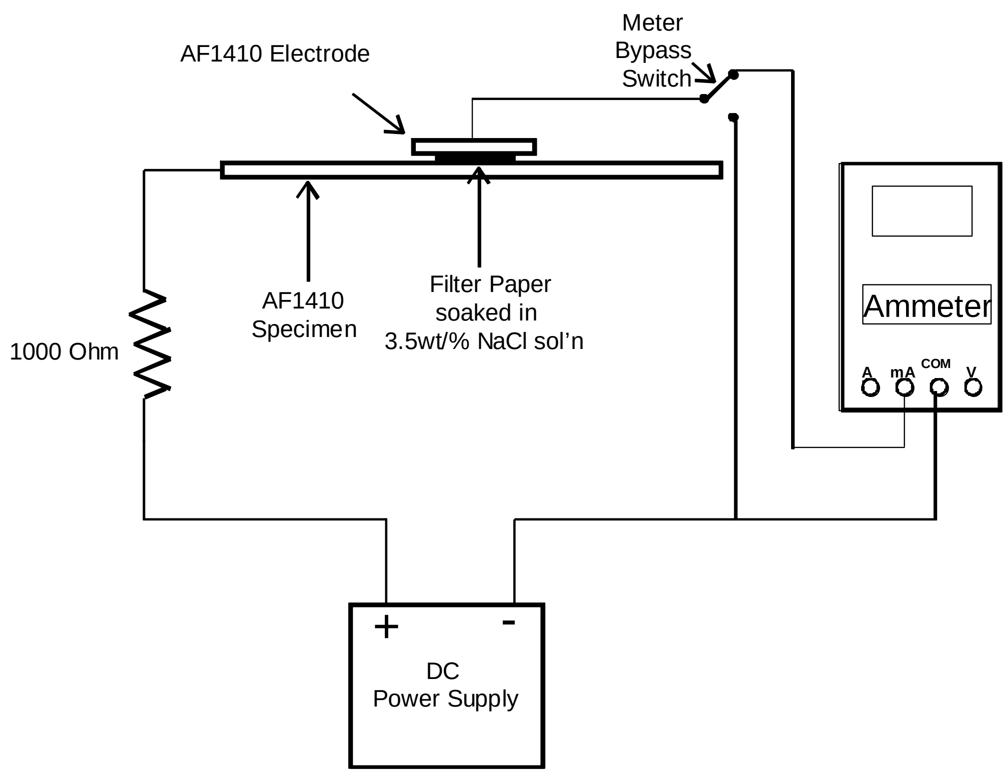

Figure 5: Schematic Diagram of the Test Setup for
Accelerated Corrosion Exposure using a Piece of Soaked Filter Paper

Three different exposure times were applied to the Batch B specimens using the UDRI technique to complete the test matrix. The exposure times used were 1.5 hr, 3 hr, and 6 hr. The procedure employed called for replacing the filter paper often to replenish the salt solution on the surface during the exposure. Preliminary testing showed that dampness of the filter paper, time between filter paper replacement, and number of times the filter paper is replaced has an impact on the surface roughness produced. Several times during the corrosion exposure when the filter paper was replaced for the corrosion-fatigue test plate specimens, it was replaced with a slightly larger piece of filter paper and the voltage was adjusted accordingly to maintain the correct current

density. Using slightly larger pieces of filter paper on successive replacements was a method determined to help blend any undercutting that may occur at the filter paper edges. The parameters used to complete the 1.5 hr, 3 hr, and 6 hr exposures, are listed in tables 4, 5, and 6. The tables include information about the filter paper replacement time, filter paper size, and voltage to use. Detailed procedures followed when performing corrosion exposures on the fatigue test plates are provided in appendix D.

Table 4: 1.5-hr Corrosion Exposure Level Parameters

Cycle	Exp. Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.9375	8.79	8.79	~12.74
5	35	55	1	10	10	~12.74
6	35	90	1.0625	11.29	11.29	~12.74

Table 5: 3-hr Corrosion Exposure Level Parameters

Cycle	Exp. Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.875	7.66	7.66	~12.74
5	40	60	0.9375	8.79	8.79	~12.74
6	60	120	1	10	10	~12.74
7	60	180	1.0625	11.29	11.29	~12.74

Table 6: 6-hr Corrosion Exposure Level Parameters

Cycle	Exp. Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.875	7.66	7.66	~12.74
5	40	60	0.875	7.66	7.66	~12.74
6	60	120	0.9375	8.79	8.79	~12.74
7	120	240	1	10	10	~12.74
8	120	360	1.0625	11.29	11.29	~12.74

In order to study the corrosion surface of the fatigue test specimens after exposure, it was necessary to remove oxides from the corroded area without causing further damage that could potentially affect the fatigue results. A method for cleaning ferrous alloys that is based on a Boeing Process Specification (P.S. 12030) for Type III Alkaline Cleaning has been successful at removing corrosion by-products on the AF1410 steel without significant observable affects to the material. Members of the Boeing team on this program have successfully used this cleaning process for similar purposes on other programs and recommended its use. The Boeing P.S. is broken down into three types according to the category of the material to be cleaned, Types I, II, and III. The Type III processes are for alkaline cleaning of ferrous, nickel, cobalt, titanium, and molybdenum alloys, and stainless steels.

UDRI adapted the process from the specification by submerging the corroded samples in a 70% concentrated solution of the Turco 4181L at approximately 190°F for up to 10 min at a time with subsequent rinsing and light mechanical rubbing of the surface. The samples were left in the bath for up to 10 min at a time, depending on the amount of corrosion byproducts. If the specimen was not cleaned after one cleaning cycle, the process was repeated.

It should be noted that, although the Boeing Process Specification indicates that Type III cleaners usually discolor or oxidize alloy surfaces, it was not a problem with the AF1410 material. Slight discolorations may have occurred on the surrounding bare material of test specimens of AF1410, but did not appear to affect fatigue test results, especially in the case of the more-severely corroded test specimens. Those discolorations may be formation of oxide that the P.S. mentions can easily occur once cleaned using the Type III process. No specific tests were performed to investigate the effects of the cleaning process itself on the baseline material behavior of the AF1410.

CORROSION SURFACE IMAGING PROCEDURES

Measurements of the topography on the Batch B fatigue test plate specimens after they were corroded and cleaned were made at the UDRI's Center for Materials Diagnostics using a WYKO NT-8000 noncontact surface profilometer. The NT-8000 is capable of using two different techniques to measure a wide range of surface heights: phase-shifting interferometry (PSI) for subnanometer resolution and vertical scanning interferometry (VSI) for larger feature measurement. The VSI technique, which allows for measurement of relatively rough surfaces from hundreds of nanometers to several millimeters, was employed to optically image and measure the topography created by the corrosion exposure on the test plate specimens. A description and comparison of several surface characterization techniques considered for measurement of the corrosion-fatigue test plates, including the optical technique of the NT-8000, can be found in reference 1.

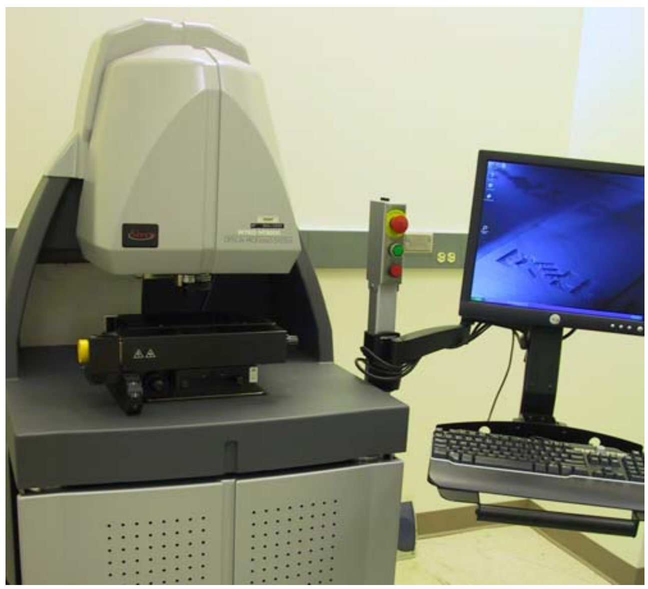

Figure 6: Photograph of the WYKO NT-8000 at the UDRI's Center for Materials Diagnostics

For the corrosion on the fatigue test plate specimens, a 2.5x objective with a 1x field-of-view (FOV) lens was used. With the optics and software options chosen for the corroded areas, the lateral resolution was 7.66 microns and the vertical resolution tended toward 0.1 microns. A single scan, or individual topographic image, obtained using the parameters described above is approximately 2.5 mm x 1.9 mm or 320 x 240 pixels in size. Using a high-accuracy motorized stage, a series of these individual scans were taken automatically on the corrosion-fatigue test plate until an 11 x 11 mm area was covered. The individual images were automatically stitched together by the software to make a larger topographic image that represented 11 mm x 11 mm of area and was approximately 1442 x 1442 pixels. Once a large stitched image was created, a stage-positioning program was implemented to move the test plate specimen under the objective lens by 10 mm to start the next 11 mm x 11 mm measurement, allowing for 1 mm of overlap.

See figure 7 for a schematic diagram of the 11 mm x 11 mm stitches overlaid on a photograph of a corrosion-fatigue test plate. Once the entire corrosion area was imaged, the 11 mm x 11 mm stitched images were manually stitched together using coordinates from the stage-positioning program. A completed topographic image of the corrosion patch on a fatigue test plate was approximately 41 mm x 41 mm (~5365 x 5365 pixels). See figure 8 for an example of a completed topographic image of a corrosion patch on a fatigue test plate. This technique of using an automatic stitching function and using a stage positioning program to increment and cover larger areas was implemented to accommodate memory constraints created by the large area of interest.

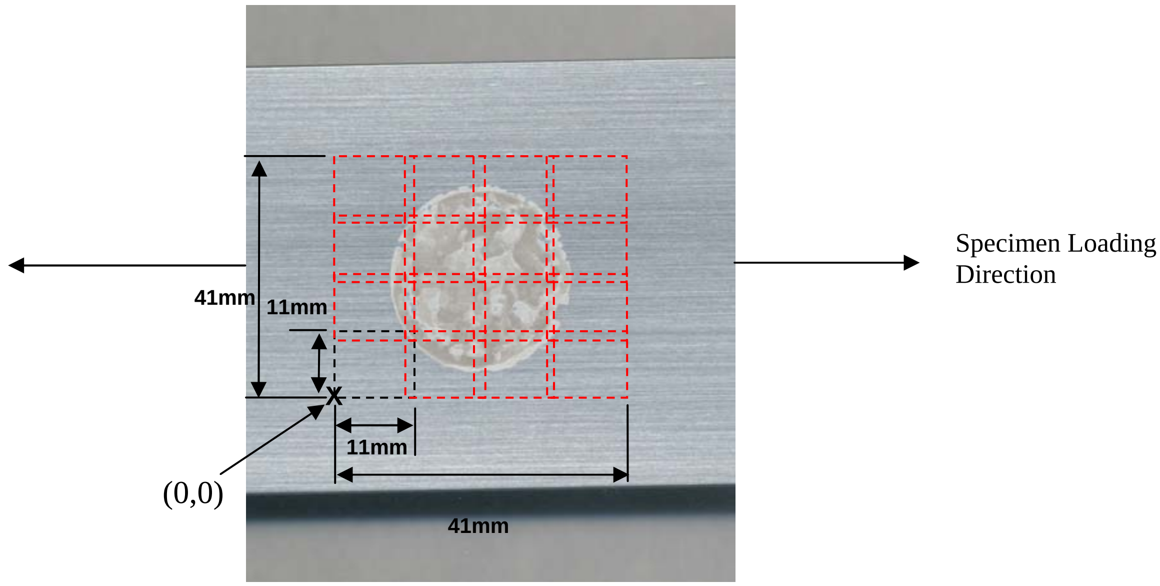

Figure 7: Schematic of the 11 mm x 11 mm Stitches of Topographic Measurements Overlaid on the Corroded Fatigue Test Plate

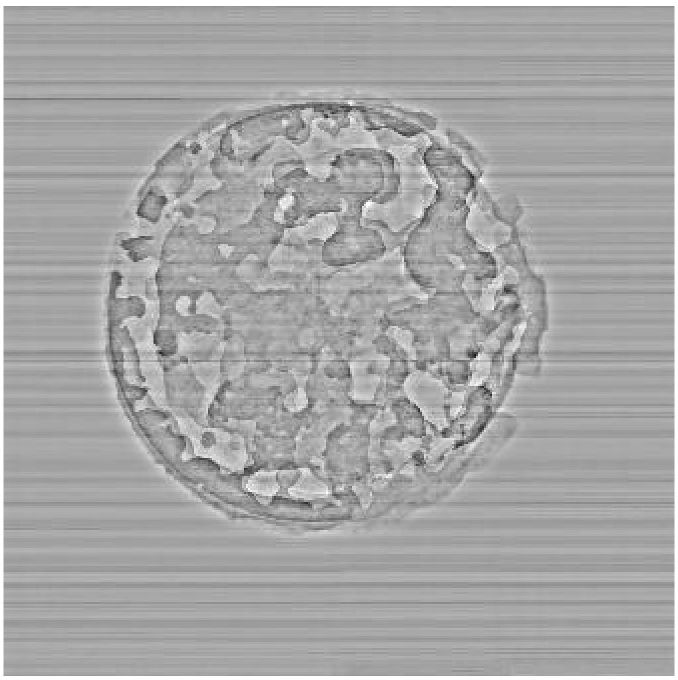

Figure 8: Example of a Completed Topographic Image of a Corrosion Patch on a Fatigue Test Plate

FATIGUE TEST LOADING

Constant-amplitude loading was specified for all AF1410 Corrosion-Fatigue plate tests to minimize spectrum effects and to provide a direct comparison to constant-amplitude probabilistic strain-life curves. Prior to corrosion-fatigue testing, the Naval Research Laboratory conducted a fractographic study of marker cycle schemes using AF1410 Compact-Tension test specimens. Several patterns using various combinations of R = 0.1 and R = 0.7 cycles were investigated, with the peak stress (P_{max}) held constant for each cycle. The marker cycle scheme that was chosen for use in the Batch B corrosion-fatigue tests gave the most visible marker patterns on the C-T fracture surfaces (figure 9). Final marker block construction and ordering is as follows:

1. Normal, constant-amplitude load cycles are completed at the specified P_{max}, R = 0.1.
2. Marker bands are made up of 400 constant-amplitude delay cycles of R = 0.7, followed by 8 constant-amplitude marker cycles of R = 0.1.
3. The maximum stress remains constant at P_{max} throughout the regular testing cycles and the marker bands.
4. Insert the required first block of marker bands after the specified number of constant-amplitude fatigue cycles at P_{max}, R = 0.1 (table 8).
5. Subsequent blocks of marker bands are introduced every 1,000 cycles in accordance with the specified schedule (table 8). The maximum number of marker bands in the entire set of marker band blocks is 7 (table 8).
6. The pattern in table 1 is repeated until final specimen fracture.

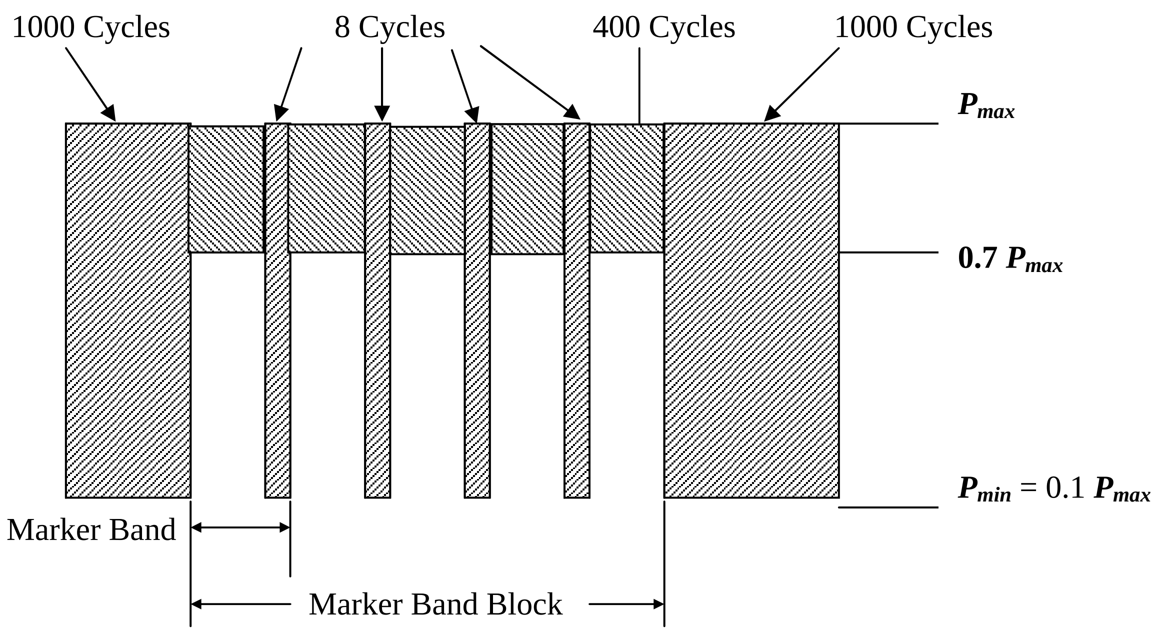

Figure 9: Four Marker Band Pattern Example

Table 8: Marker Band Schedule

Block No.	Constant-Amp. Cycles	Marker Bands at End of Block	Marker Cycles	Total Cycles
1	1,000	3	1,624	2,624
2	1,000	5	2,440	6,064
3	1,000	7	3,256	10,320
4	1,000	4	2,032	13,352
5	1,000	6	2,848	17,200
Repeat Blocks 1 to 5	1,000	Restart pattern at 3		

The number of bands in successive marker blocks is ordered nonsequentially to aid in distinguishing between adjacent block marker values on the fracture surface. An example of the marker block visibility on a fracture surface is shown in figure 10.

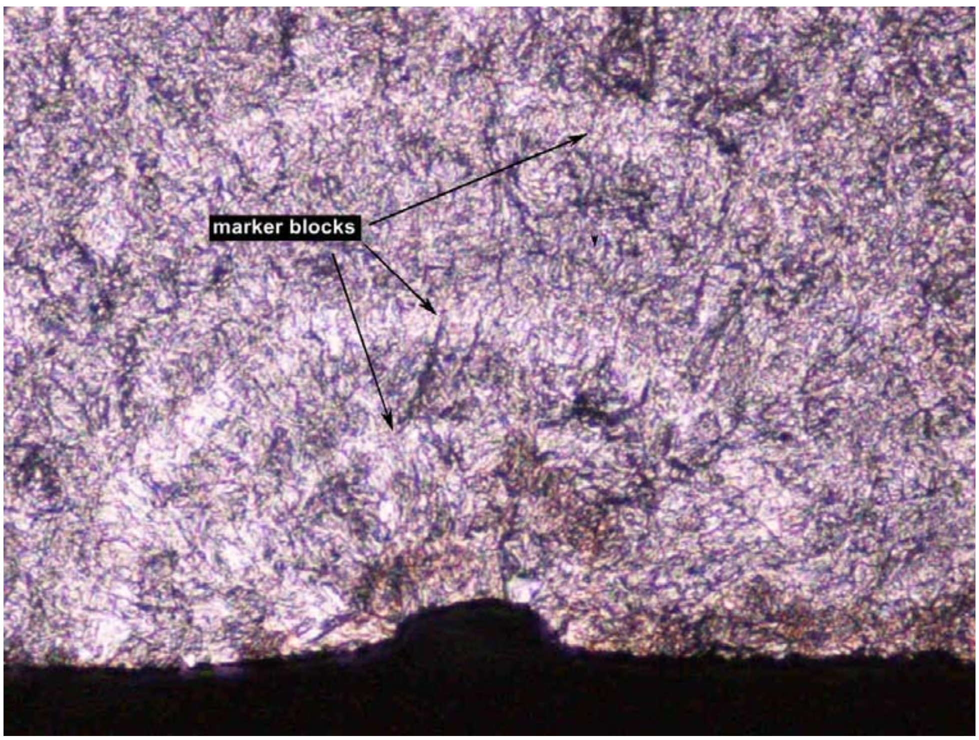

Figure 10: Fracture Surface of Critical Crack on Specimen 614-1

CRACK DEPTH MEASUREMENT

Post-test Quantitative Fractography (QF) was utilized to measure crack depths for estimating the crack initiation life of failed test specimens. The method used to take depth measurements on the specimen fracture surfaces is shown schematically in figure 11.

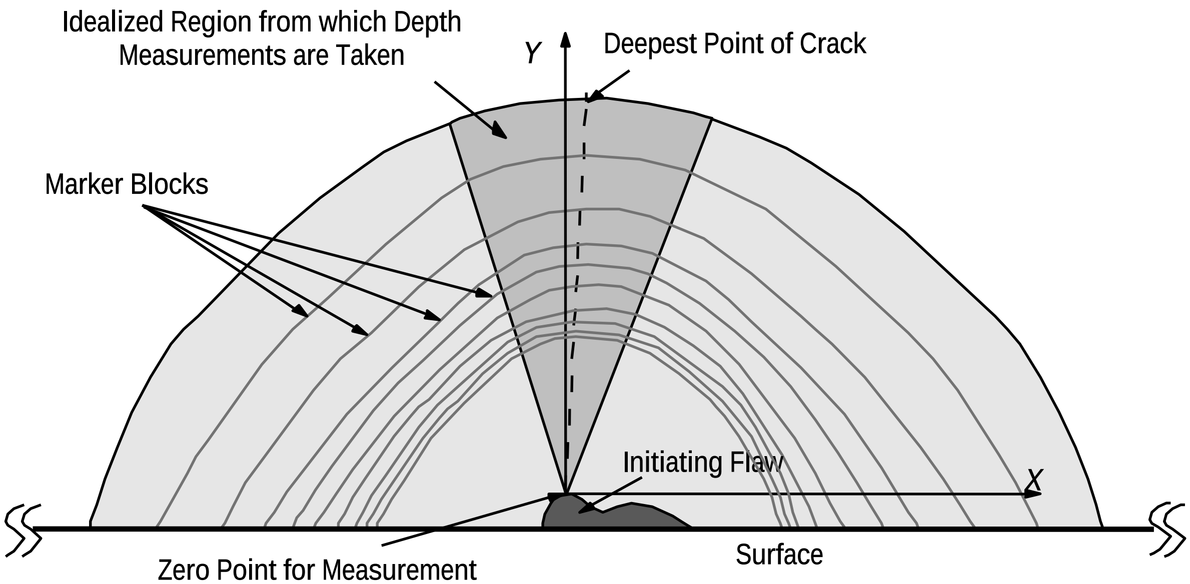

Figure 11: QF Crack Depth Measurement Schematic

For all specimens tested with corrosion on the surface, the origin of the crack depth measurements was set to the maximum depth of the surface flaw that initiated the critical crack in the test specimen. This convention was used to avoid the possibility of double-counting the initiating flaw depth when combining the White Light Interferometry data with QF based life predictions. The same approach was also applied to uncorroded test specimen crack origins. For all specimens, crack depth measurements were taken at the beginning and end of each marker block, from the smallest depths that the marker block boundaries were clearly distinguishable on the fracture surface to the depth that the crack transitions to growth on the shear plane. An example of QF crack depth measurements for a test specimen is plotted in figure 12.

Crack initiation is defined as the life to a 0.010 in. crack depth. For the Batch B test specimens, the number of cycles to crack initiation is linearly interpolated using the cycle and log crack depth values of the two QF measurements that bracket 0.010 in. All final test results are presented as life to crack initiation.

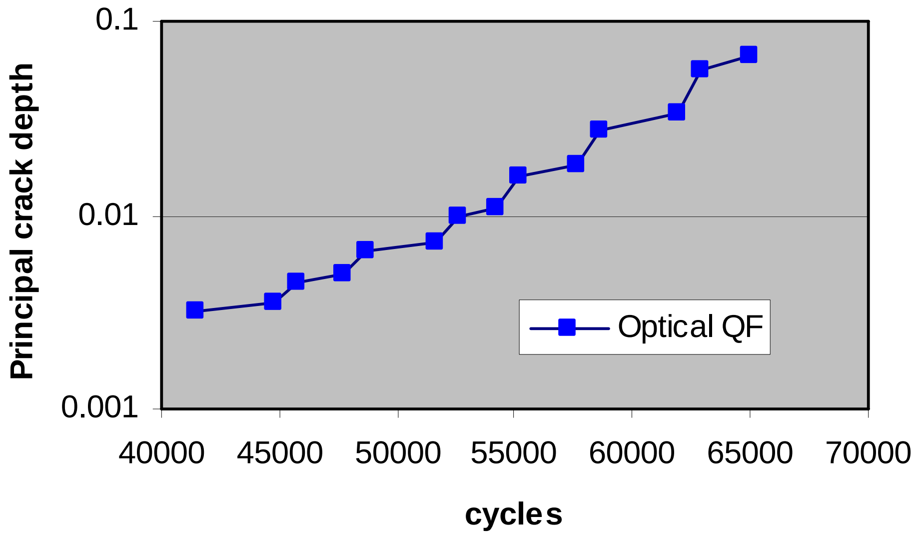

Figure 12: Crack Growth Curve for Specimen 547-46C, 170 ksi Maximum Stress

NOTCH DIMENSION MEASUREMENTS

The following guidelines were created for measurement of corrosion notch dimensions to minimize scatter in corrosion-fatigue notch ratio modeling.

Single Notch

Measure the notch width in a direction perpendicular to the applied loading. Measure the notch height in a direction parallel to the applied loading. Measure the notch depth on the fracture surface from a reference plane extending across the plate surface near the notch edges, to the maximum depth of the notch.

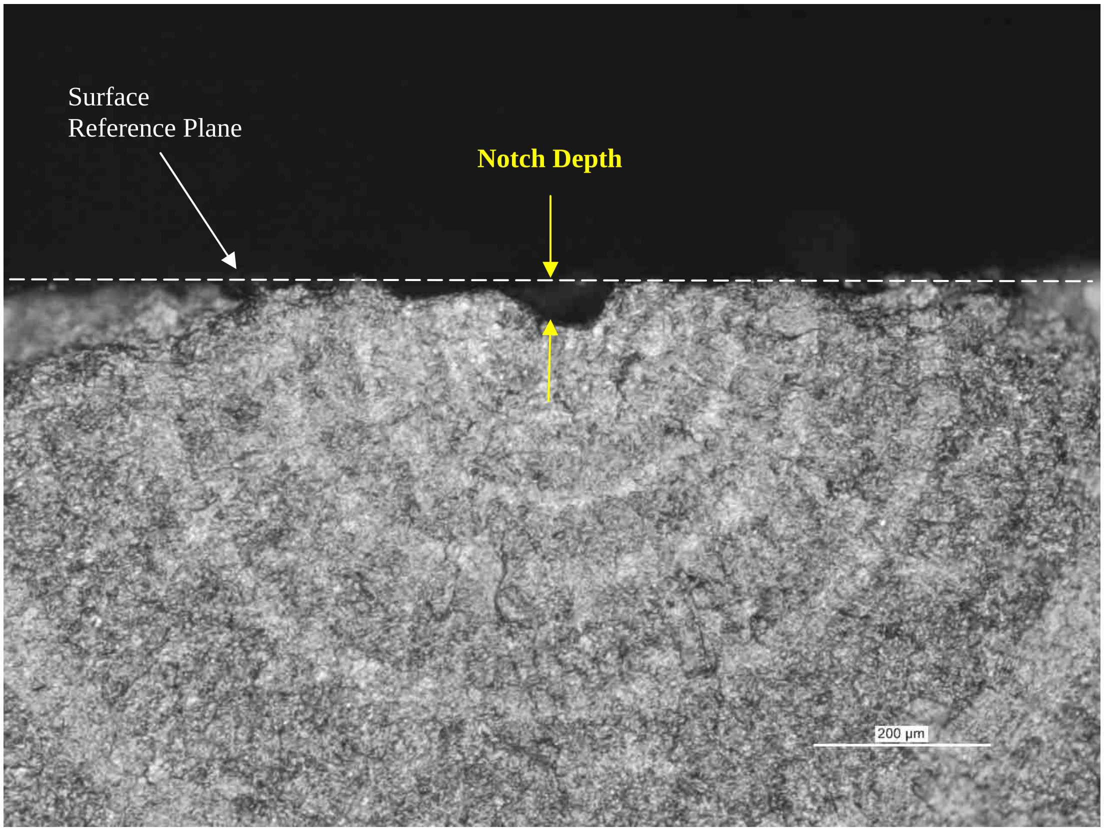

Figure 13: Single Notch Depth, Fracture Surface

Multiple Notches

For two or more notches interacting with each other in a line perpendicular to the loading direction:

1. Measure the combined notch depth on the fracture surface from a reference plane extending across the plate surface near the combined notch edges, to the maximum depth of the deepest notch.

2. Measure the height of the combined notch as the height of the deepest notch in the series of notches.

3. The combined notch width is measured as the width of all of the notches in the series.

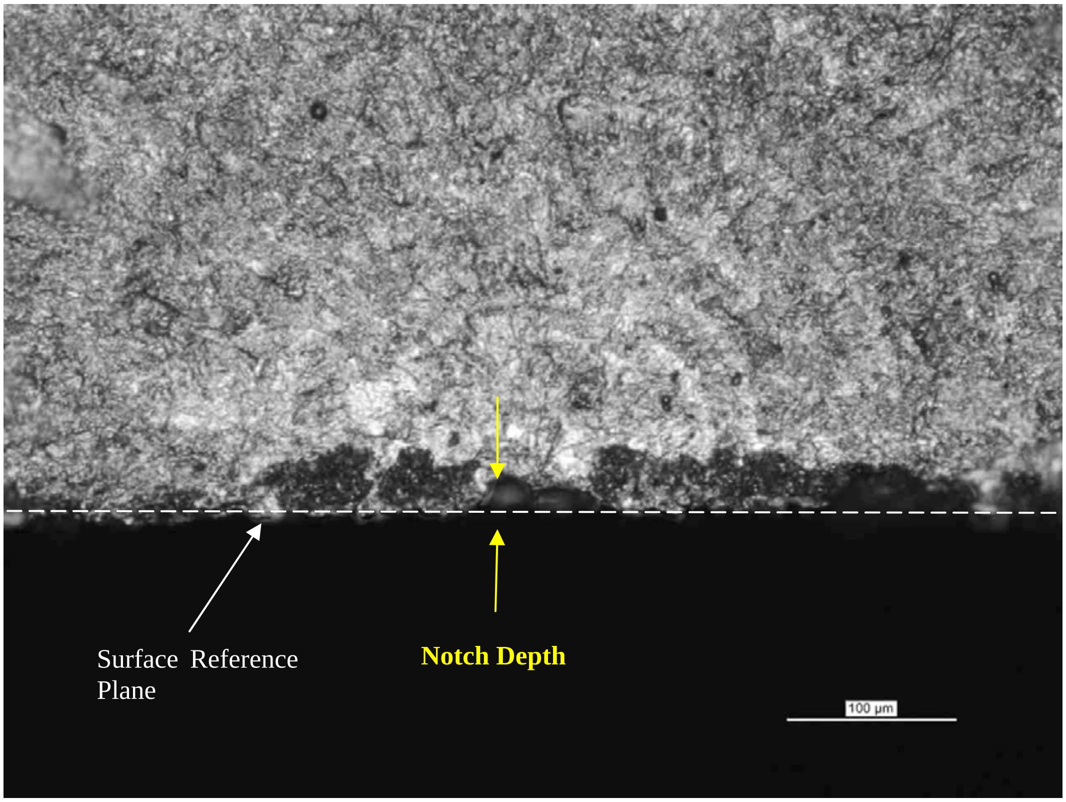

Figure 14: Multiple Notch Depth, Fracture Surface

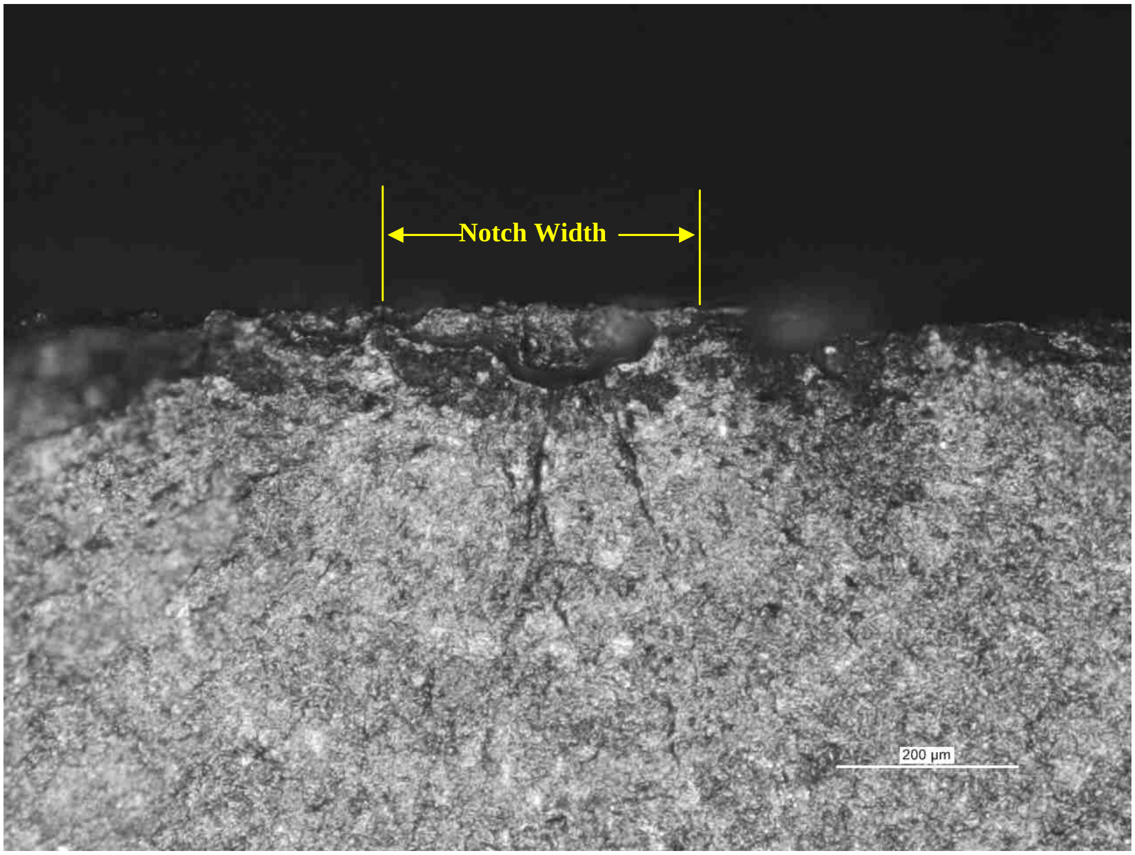

Figure 15: Multiple Notch Width, Fracture Surface

SURFACE CRACK DETECTION

The optical microscope that NAVAIR used to perform QF work on corrosion-fatigue plates was also used to detect surface cracks that did not reach critical size before the test specimen failed. A flourescence illuminator with a filter slider is attached to the microscope and used to illuminate a failed specimen that has been sprayed with flourescent dye penetrant. The dye penetrant is wicked into the surface cracks and glows when hit with the ultraviolet light from the illuminator. This technique allows the detection of very small cracks over a large surface area, with a high degree of magnification.

DATA AND DISCUSSION

TEST SPECIMEN MECHANICAL PROPERTIES

An initial set of nine fracture toughness tests were performed for the Batch B material in room temperature laboratory air in accordance with reference 2. Results from these tests are listed in table 9.

Table 9: Initial Fracture Toughness Tests for AF1410 Batch B Material

Specimen ID	Plane-Strain Fracture Toughness (ksi√in.)
STL461-8	114
STL461-13	114
STL461-25	118
STL461-26	119
STL461-28	124
STL461-29	128
STL461-30	121
STL461-31	131
STL461-32	112
Average	120

All tests met the validity criteria of reference 2; however, only one test met the minimum fracture toughness requirements of 130 ksi√in. from the Boeing MMS 214 material specification (reference 4). An investigation by the NAVAIR Materials Laboratory (AIR-4.3.4) of a section of the Batch B material billet indicated that the average Rockwell C hardness (HRC) of 44 was well above the maximum hardness of 36 HRC specified for normalized and overaged bar and forgings in reference 4 (reference 5). Microstructural analysis of the billet section showed that the material had not been heat treated prior to purchase by NAVAIR. It was thus assumed that the material had not been sufficiently overaged. Before cutting any corrosion-fatigue specimen blanks from the billet, the entire billet was sent to the Dayton Forging and Heat Treating Company by UDRI for additional overaging. No additional normalization was performed. For overaging, the billet was heated to 1,250 ±25°F for a minimum of 6 hr, and then air cooled to room temperature per reference 4. Following the additional overaging step, the average hardness for the billet was measured to be 31-32 HRC, which was below the specified maximum. Additional fracture toughness blanks, fatigue crack growth rate, and corrosion-fatigue specimen blanks were then cut from the overaged billet. These blanks were all heat treated in a single batch by Hercules, and included three tensile travelers. The tensile travelers were machined from a different heat of AF1410 material, and so are not fully representative of the tensile properties of the Batch B test specimens. One tensile coupon was tested by Hercules, and the other two were tested at UDRI. All tests were performed at room temperature per ASTM E8 (reference 6). The first tensile test at UDRI (STL533-12) was performed on an 11 kip test frame, which did not have enough load capacity to complete the test. The specimen was subjected to a peak load

corresponding to a maximum stress of 200 ksi., which is below the nominal proportional limit. This coupon was then subsequently tested to failure on a 22 kip load frame. Test results on the tensile travelers are shown in table 10, and demonstrate that the individual tests all exceeded minimum strength and yield requirements per reference 4.

Table 10: Test Results from AF1410 Batch B Heat Treat Tensile Travelers

Specimen	Test Lab	Estimated Elastic Modulus (Msi)	0.2% Offset Yield Strength (ksi)	Tensile Strength (ksi)
STL533-12	UDRI	27.4	236.8	250.8
STL533-3	UDRI	27.7	228.6	249.8
-	Metcut	-	223.3	254.0
Average		27.6	229.6	251.5

Four plane-strain fracture toughness coupons that were cut from the overaged Batch B billet were tested by UDRI after heat treatment, per reference 2. Results are shown in table 11. The test of coupon STL532-1 was invalid due to the crack length at the start of the test being too long. All other tests met the validity criteria of reference 2.

Table 11: Plane-Strain Fracture Toughness of Overaged AF1410 Batch B Material

Specimen	Plane-Strain Fracture Toughness (ksi√in)
STL532-1	Invalid
STL532-2	104
STL536-1	106
STL536-2	107
Average	105.7

The average fracture toughness for the overaged coupons was significantly lower than for the initial set of Batch B fracture toughness tests, and well below the minimum fracture toughness requirements of 130 ksi√in. from reference 4. Inability of the Batch B material to meet minimum fracture toughness requirements was not considered critical for the purposes of the corrosion-fatigue test program, because the principle interest in the fatigue behavior of test specimens was the life to crack initiation, and not final failure. The reduced fracture toughness of the overaged material was such that crack initiation would still occur well before the critical crack size was reached, so the crack initiation lives of the test specimens would not be affected by the fracture toughness values of the material.

Because of the reduced plane strain fracture toughness values of the overaged Batch B material, concern was raised that the crack growth behavior of the material may also be affected. Significant deviations from nominal crack growth behavior would have an effect on the crack initiation lives of the corrosion-fatigue test specimens. To investigate this possibility, additional crack growth testing was performed on C(T) specimens cut from the overaged Batch B billet. Six C(T) specimens were machined from blanks that were heat treated along with the corrosion-fatigue specimen blanks and second set of fracture toughness blanks. Crack growth tests were performed using the constant force amplitude procedure of reference 3, in laboratory air. Three specimens each were tested at values of R = 0.1 and R = 0.5. Results of those tests are shown in figure 16. The reduced test data values are also listed in tabular form in appendix E.

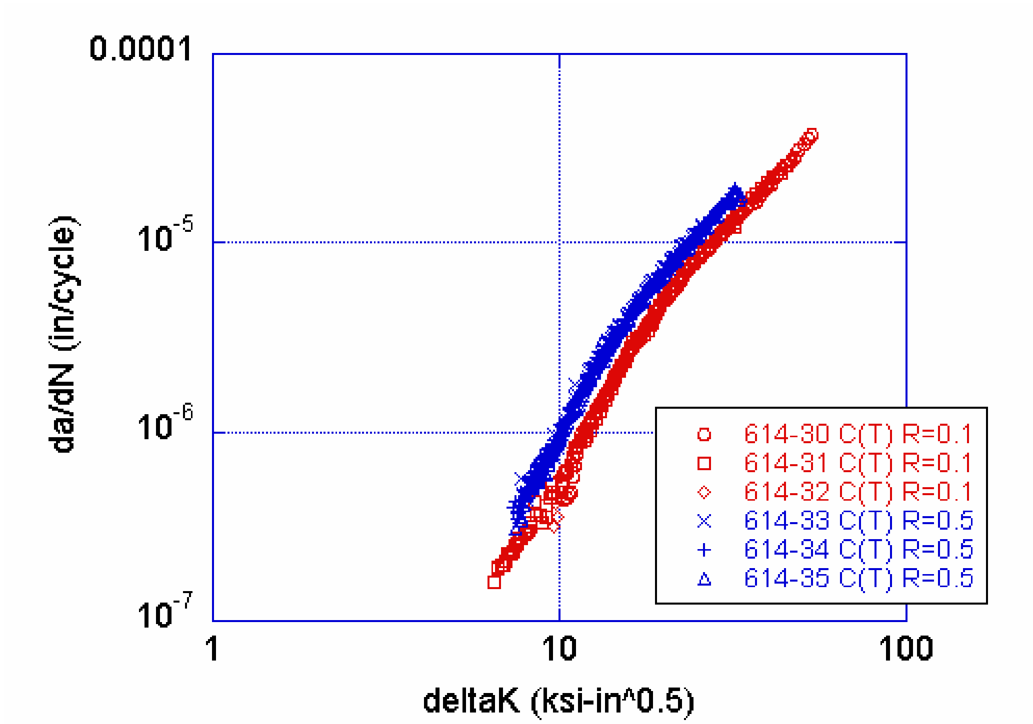

Figure 16: Fatigue Crack Growth Rate Test Results for Overaged AF1410 Batch B C(T) Specimens

A comparison of the Batch B FCGR tests results with the equivalent tests using Batch A material coupons is shown in figure 17. Only small differences in crack growth rate are apparent between the two batches of material, indicating that the crack growth rates and crack initiation lives of the Batch B corrosion-fatigue specimens should be comparable to those of the Batch A tests.

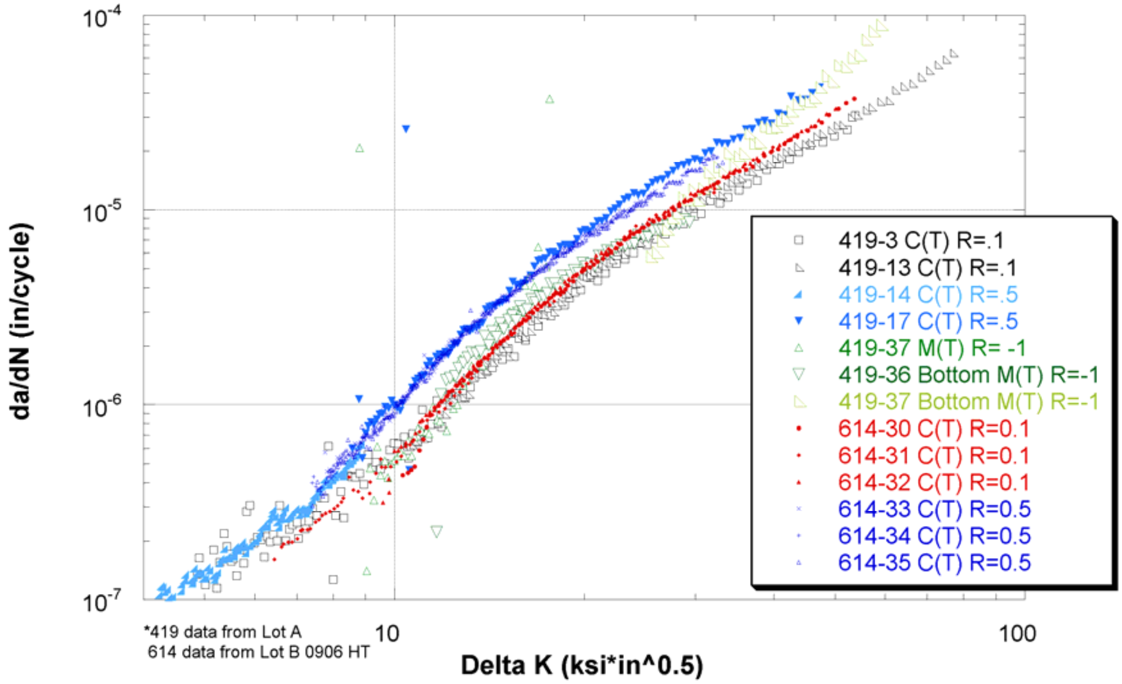

Figure 17: Comparison of Fatigue Crack Growth Rate Test Results from AF1410 Batch A and Overaged Batch B Material Stock

CORROSION-FATIGUE SPECIMEN TESTS

A total of 62 corrosion-fatigue tests was performed on AF1410 Batch B plate specimens, with 17 tests on uncorroded plates and the remainder on corroded plates. The test matrix was divided up between the UDRI Structural Test Laboratory and the NAVAIR Materials Test Laboratory (AIR-4.3.4). All NAVAIR specimens were tested under load control in a 220 kip MTS test frame, using the constant-amplitude marker band spectrum described previously. The test frequency was 2 Hz. The test frame used a 220 kip MTS load cell with a 100 kip calibration, 110 kip hydraulic grips and an Instron 8800 servo-hydraulic controller. Post-test calibration of the load cell indicated no deviation from nominal loading, so no corrections to the test data were necessary. All UDRI specimens were tested under load control in a 220 kip MTS test frame, using the constant-amplitude marker band spectrum described previously. The test frequency was 4 Hz. The test frame used a 220 kip MTS load cell calibrated to 220 kip, 220 kip hydraulic grips, an MTS Teststar II servo-hydraulic controller, and UDRI developed (LabView 6.2) spectrum generator.

Because of the slow frequency of testing due to the large actuator size, the runout for fatigue testing was reduced from 1×10^7 cycles to 1×10^6 cycles to enable testing of a single specimen to be completed in a reasonable amount of time. Maximum stress for corrosion-fatigue testing varied from 160 to 200 ksi, with two uncorroded specimens tested at lower peak stresses. Crack initiation lives for the Batch B specimen tests are shown in figure 18. Results for the uncorroded

Batch B specimens are listed in table 12. Results for the corroded specimens are listed in tables 13, 14, and 15 for the three different exposure levels.

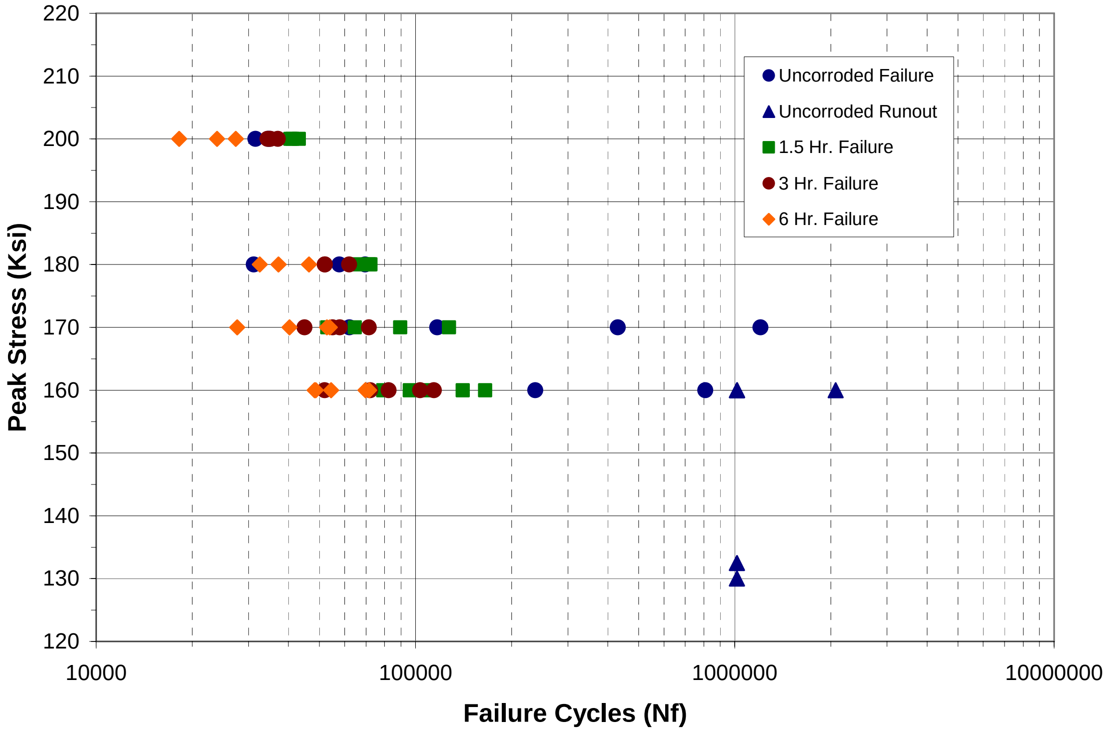

Figure 18: Life to Crack Initiation for AF1410 Batch B Corrosion-Fatigue Tests

Table 12: Uncorroded AF1410 Batch B Corrosion-Fatigue Plate Test Results

Specimen No.	Test Facility	Peak Stress (ksi)	Crack Init. (cycles)	Total Life (cycles)	Critical Crack Location
547-15D	NAVAIR	160	237,378	251,736	surface
547-28C	NAVAIR	160	808,962	826,109	surface
544-6C	UDRI	170	62,067	75,600	surface
545-4B	UDRI	170	1,203,735	1,217,635	surface
545-7B	UDRI	170	429,926	442,986	surface
547-27D	UDRI	170	117,057	126,796	surface
545-8D	UDRI	180	69,628	82,536	surface
547-11A	UDRI	180	31,142	40,503	surface
547-24B	UDRI	180	57,732	65,616	surface
545-9D	NAVAIR	200	31,547	41,437	surface
547-25C	NAVAIR	200	34,582	42,700	surface
547-34B	NAVAIR	200	34,932	42,312	surface
Runouts					
544-7B	NAVAIR	160		2,069,433	-
547-40B	NAVAIR	160		1,017,006	-
545-5C	NAVAIR	160		1,014,944	-
547-45C	UDRI	132.5		1,014,800	-
547-51D	UDRI	130		1,014,800	-

Table 13: 1.5-hr Corrosion-Fatigue Plate Test Results

Specimen No.	Test Facility	Peak Stress (ksi)	Crack Init. (cycles)	Total Life (cycles)	Critical Crack Location
544-9C	UDRI	160	79,374	95,083	corrosion
545-3D	UDRI	160	140,711	158,141	corrosion
547-7B	UDRI	160	165,317	182,427	corrosion
547-26A	UDRI	160	96,069	113,645	corrosion
547-44C	UDRI	160	110,506	131,130	corrosion
545-2A	NAVAIR	170	64,581	81,038	corrosion
547-39D	NAVAIR	170	89,580	104,179	corrosion
547-46C	NAVAIR	170	52,978	68,983	corrosion
547-50B	NAVAIR	170	127,432	143,914	corrosion
614-2	NAVAIR	180	65,523	82,318.5	corrosion
614-22	NAVAIR	180	72,305	88,947	surface
614-25	NAVAIR	180	71,626	86,696.5	surface
614-7	UDRI	200	41,141	52,232	corrosion
614-11	UDRI	200	40,591	51,292	corrosion
614-17	UDRI	200	43,152	52,418	corrosion

Table 14: 3-hr Corrosion-Fatigue Plate Test Results

Specimen No.	Test Facility	Peak Stress (ksi)	Crack Init. (cycles)	Total Life (cycles)	Critical Crack Location
545-6A	UDRI	160	114,168	132,719	corrosion
545-10D	UDRI	160	51,988	69,269	corrosion
547-22C	UDRI	160	72,125	91,153	corrosion
547-37B	UDRI	160	82,424	99,016	corrosion
547-9M	UDRI	160	103,392	120,425	corrosion
547-5A	NAVAIR	170	71,468	86,147	corrosion
547-48D	NAVAIR	170	54,995	71,537	corrosion
547-23B	NAVAIR	170	44,960	57,713	corrosion
544-5C	NAVAIR	170	57,903	72,400	corrosion
614-4	NAVAIR	180	52,069	67,360	corrosion
614-12	NAVAIR	180	52,009	66,768	corrosion
614-21	NAVAIR	180	62,035	77,282	corrosion
614-1	NAVAIR	200	34,403	45,507	corrosion
614-15	NAVAIR	200	37,046	48,068	corrosion
614-18	NAVAIR	200	35,116	44,398	edge

Table 15: 6-hr Corrosion-Fatigue Plate Test Results

Specimen No.	Test Facility	Peak Stress (ksi)	Crack Init. (cycles)	Total Life (cycles)	Critical Crack Location
544-8C	UDRI	160	48,289	64,961	corrosion
544-10C	UDRI	160	54,416	71,633	corrosion
547-6A	UDRI	160	69,676	88,890	corrosion
547-20B	UDRI	160	71,566	88,885	corrosion
547-36B	UDRI	160	48,724	71,337	corrosion
544-3B	NAVAIR	170	27,634	40,391	corrosion
547-16B	NAVAIR	170	40,276	51,763	corrosion
547-2C	NAVAIR	170	53,899	65,754	corrosion
547-31B	NAVAIR	170	52,833	67,060	corrosion
614-3	UDRI	180	46,378	61,800	corrosion
614-8	UDRI	180	37,236	48,807	corrosion
614-13	UDRI	180	32,523	45,608	corrosion
614-5	UDRI	200	23,913	34,817	corrosion
614-6	UDRI	200	18,178	27,785	corrosion
614-19	UDRI	200	27,389	34,418	corrosion

All of the plates that failed during testing cracked inside the gage area of the specimen. The uncorroded plates all had critical cracks that initiated from small gouge marks on the specimen surfaces, most likely from the grinding operation during specimen manufacture. An example of the machining damage that initiated cracks in the uncorroded specimens is shown in figure 19. Some of the corroded plates that were tested cracked outside the corrosion patch. For these

plates, the surface defects on the uncorroded portion of the plates had a high enough stress concentration to override the local stress concentrations due to the corrosion. The general locations of the critical cracks on all test specimens that failed are noted in the tables. For the corroded specimens that cracked in the corrosion patch, all of the cracks initiated from small semi-elliptical notches that formed as a result of the corrosion process (figure 20), except for the critical crack on specimen 547-7B.

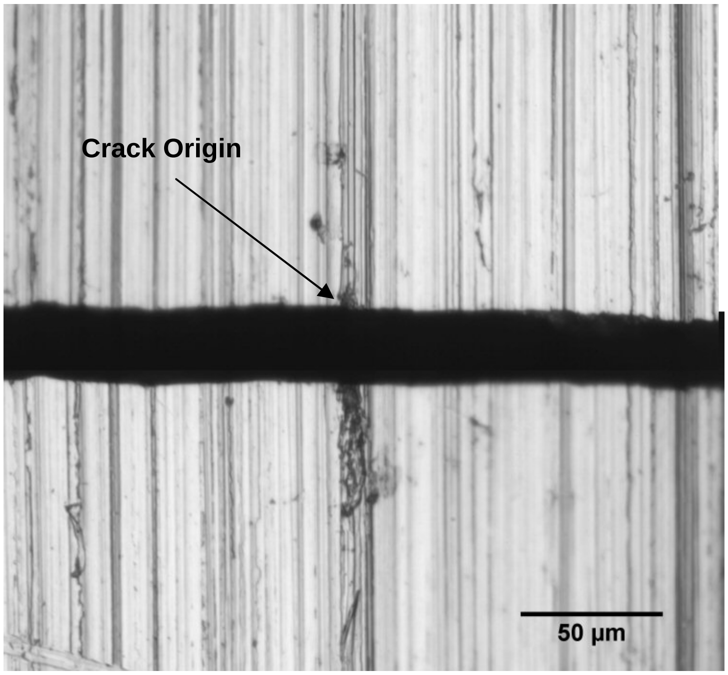

Figure 19: Machining Anomaly on the Surface of a Failed Fatigue Test Plate

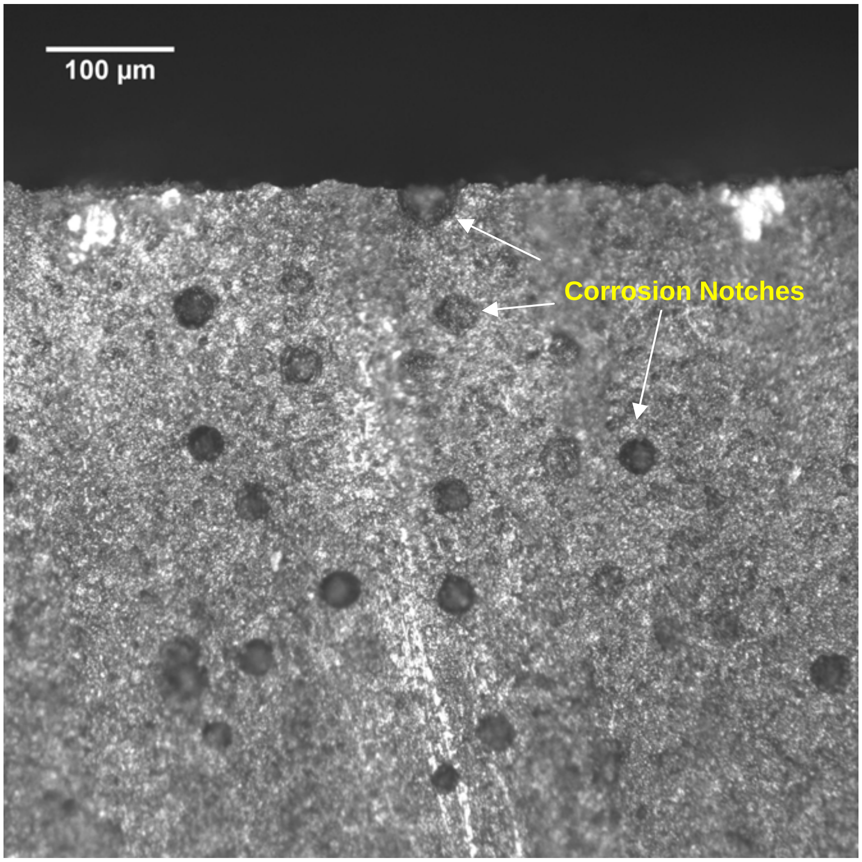

Figure 20: Corrosion Notches on the Surface of a Failed C-F Plate

Optically measured dimensions of the critical notch for each corroded specimen are listed in tables 16, 17, and 18. The X and Y coordinate locations of the critical notch with respect to the WLI image of the corrosion patch are also listed in the tables. The locations are found by carefully examining the surface topology adjacent to the critical notch, and comparing it to the WLI topology in that area of the corrosion patch. For the NAVAIR tested plates, surface cracks that did not reach critical size before the plate failed were detected using flourescent dye penetrant. The overall surface crack lengths were measured and are listed in the tables for the respective test specimen. WLI coordinate locations for these cracks were not recorded. Critical notch dimensions for all of the uncorroded plates that failed were also recorded for comparison to the critical corrosion notches, and are listed in table 19.

Table 16: 1.5-hr Exposure C-F Plate Critical Notch Size and Location

		Notch Location WLI Coord. System		Crack	Combined Notch Dimensions		
Specimen	Test Lab	X' (µm)	Y' (µm)	Length (mm)	Width (µm)	Height (µm)	Depth (µm)
544-9C	UDRI	14,875	23,714		28.9	35	19
545-3D	UDRI	16,016	15,442		20.5	28.6	18.5
547-26A	UDRI	31,005	21,439		38	85.7	20.8
547-44C	UDRI	25,200	11,175		67.7	23.8	13.8
545-2A	NAVAIR	24,909	26,242	3.95 1.646 1.292 0.39 0.38 0.38 0.304 0.186	66	45	18
547-39D	NAVAIR	33,074	21,538	0.313 0.282 0.216	30	29.2	9
547-46C	NAVAIR	11,910	24,210	0.604	31.8	24.2	10
547-50B	NAVAIR	15,074	27,750	1.276 0.85 0.7732	30	27.2	11.6
614-2	NAVAIR	27,400 20,297	14,800 25,100	0.322	19.4	20.8	10.2
614-22	NAVAIR	failure occurs outside of corrosion patch no cracks found in corrosion patch					
614-25	NAVAIR	failure occurs outside of corrosion patch 25,950 27,800	9,910 16,700	2.33 0.68			

Table 16: (Cont'd)

Specimen	Test Lab	Notch Location WLI Coord. System X' (µm)	Notch Location WLI Coord. System Y' (µm)	Crack Length (mm)	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
614-7	UDRI	20,780	20,459		55	33	10.3
		13,764	18,873		31.9	46.5	8.5
614-11	UDRI	11,558	21,876		44.4	28.5	7.9
		13,427	22,343		47.1	20.1	6
		33,350	22,680		64.5	44.2	12.4
		24,572	22,274		20	19.6	9
		27,582	22,067		19.5	20.2	9.9
614-17	UDRI	21,577	29,006		22.1	20.8	12.5
		16,951	26,463		47.3	25	10.4
		19,946	29,252		21	17.7	11.1
		24,610	26,808		82.7	36.4	11.8
		14,162	27,957		24.7	34.8	6.8
		13,388	28,049		21.4	32.4	10.4

Table 17: 3.0-hr Exposure C-F Plate Critical Notch Size and Location

Specimen	Test Lab	Notch Location WLI Coord. System X' (µm)	Notch Location WLI Coord. System Y' (µm)	Crack Length (mm)	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
545-6A	UDRI	29,749.91	26,624.68		35.2	35.1	11.3
		31,496.3	20,236.68		48.1	22.8	16.8
545-10D	UDRI	25,475.74	33,640.85		38.2	37.5	20.6
547-22C	UDRI	20,282.55	24,840		38.4	40.6	16.8
547-37B	UDRI	17,877.45	22,480.85		24.7	32.5	13.6
		22,404.26	23,354.04		29.1	31	17.6
547-9M	UDRI	26,440.96	27,260.43		41.4	37.9	10.8
547-5A	NAVAIR	21,500	24,400		35	25	22.8
		19,500	29,700	1.55			
		16,800	25,600	1.46			
547-48D	NAVAIR	24,900	23,900		65.4	41.2	22
547-23B	NAVAIR	32,400	15,700		74.4	40	24
		24,700	19,200	6.1			
		15,600	16,800	4.26			
544-5C	NAVAIR	12,630	18,766		47	31	13
				0.64			
				0.248			
614-4	NAVAIR	20,320	11297		24.4	24.4	12.2
		34,350	17,340	1.201			
		31,480	16,690	0.6926			
		33,900	22,300	0.6544			
		31,800	20,440	0.6196			
614-12	NAVAIR	29,800	21,900		37	59	26
		34,560	12,860	1.046			
		25,621	10,531	0.467			
		12,400	15,250	0.359			
		11,700	16,060	0.192			
		21,600	23,300	0.1552			
614-21	NAVAIR	20,895	30,768		27	26.6	7.6
		15,817	12,900	1.688			
		18,850	9,780	1.04			
		17,057	30,270	1.011			
		22,879	21,423	0.55			
		23,600	21,400	0.49			

Table 17: (Cont'd)

Specimen	Test Lab	Notch Location WLI Coord. System X' (µm)	Notch Location WLI Coord. System Y' (µm)	Crack Length (mm)	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
614-1	NAVAIR	27,950	22,570		41	43.2	18
		13,657	16,866	1.877			
		22,800	26,840	1.717			
		16,705	25,518	1.55			
		23,780	25,400	1.33			
		33,480	15,097	1.13			
		30,929	21,316	1.054			
		21,980	11,596	0.876			
		12,477	16,743	0.804			
		13,400	23,515	0.76			
		59 additional cracks found					
614-15	NAVAIR	23,354	9,566		23	24.2	7.4
		30,400	28,860	3.368			
		32,230	23,070	2.47			
		19,409	30,148	2.17			
		19,340	18,650	1.58			
		32,790	17,678	1.525			
		17,300	18,500	1.1			
		17,110	15,227	1			
		18,735	14,369	0.972			
		29,137	22,503	0.9346			
		13 additional cracks found					
614-18	NAVAIR	failure occurs outside of corrosion patch					
		19,600	17,080	6.15			
		24,340	15,200	3.64			
		28,600	25,300	2.83			
		27,700	17,400	2.64			
		22,740	17,390	1.449			
		24,300	16,880	0.98			
		19,922	13,350	0.625			
		19,100	13,100	0.6118			
		20,634	13,166	0.461			
		18,400	13,090	0.407			
		9 additional cracks found but stopped counting					

Table 18: 6.0-hr Exposure C-F Plate Critical Notch Size and Location

Specimen	Test Lab	Notch Location WLI Coord. System X' (µm)	Notch Location WLI Coord. System Y' (µm)	Crack Length (mm)	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
544-8C	UDRI	29,283	13,435		180.9	67.5	21.7
544-10C	UDRI	13,328	16,177		37.8	50.6	21.5
		22,282	16,905		47.6	51.6	17.4
547-6A	UDRI	20,436	24,901		31.7	28.5	6.7
547-20B	UDRI	32,668	17,533		89.4	43.5	16.4
547-36B	UDRI	16,782	28,440		42.8	12.2	10.6
		15,679	28,785				
		17,364	28,517				
		19,517	28,279				
544-3B	NAVAIR	20,167	32,292		99	109	47.6
		17,119	31,228				
		24,,200	32,492				
		28,400	25,575	1.1866			
		27,800	30,186	0.577			
		30,700	26,300	0.48			
		30,700	27,850	0.3888			
		32,000	24,000	0.3626			
		22,300	30,500	0.34			
		28,030	28,550	0.33			
		30,100	24,400	0.32			
547-16B	NAVAIR	12,900	20,750		41	37	12.4
547-2C	NAVAIR	27,100	8,400		49	43.2	14
		20,500	7,690				
		27,200	8,500				
		25,320	27,137	4.375			
		18,400	26,870	1.69			

Table 18: (Cont'd)

Specimen	Test Lab	Notch Location WLI Coord. System X' (µm)	Notch Location WLI Coord. System Y' (µm)	Crack Length (mm)	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
547-31B	NAVAIR	28,540	23,450		33.4	35.2	18
		24,700	24,470				
		15,260	10,420				
		21,180	16,670	2.74			
		20,200	6,220	2.2			
		30,600	16,630	0.946			
		21,250	9,370	0.4			
		22,800	27,000	0.33			
		20,200	31,100	0.28			
		23,177	17,860	0.279			
		5 additional cracks found					
614-3	UDRI	17,785.53	9,360		106.4	42.4	14.8
614-8	UDRI	33,104.68	18,765.96		33.2	38	12.7
614-13	UDRI	12,691.91	12,178.72		87.1	54.2	12.1
614-5	UDRI	14,476.6	25,506.38		78.5	44	11.6
614-6	UDRI	30,416.17	20,925.96		146.9	47.2	22.9
614-19	UDRI	26,969.36	28,470.64		30.1	42.6	10.6

Table 19: Critical Notch Dimensions for Uncorroded C-F Test Plates

Specimen	Test Lab	Combined Notch Dimensions Width (µm)	Combined Notch Dimensions Height (µm)	Combined Notch Dimensions Depth (µm)
547-15D	NAVAIR	41.4	75.8	20
547-28C	NAVAIR	20.4	7.8	-
544-6C	UDRI	81.3	37.0	18.0
545-4B	UDRI	8.4	13.6	3.5
545-7B	UDRI	10.3	3.8	3.2
547-27D	UDRI	112.0	-	67.5
545-8D	UDRI	37.0	19.6	11.3
547-11A	UDRI	107.4	21.2	5.1
547-24B	UDRI	66.3	56.4	7.3
545-9D	NAVAIR	61.2	83.8	15.2
547-25C	NAVAIR	56	52	18
547-34B	NAVAIR	54	18	6.8

The critical crack on specimen 547-7B originated inside the corrosion patch, but did not appear to be the result of any corrosion-induced notch or surface machining defect. Instead, the initiating feature appears to be surface transverse microcracking that runs along the loading direction of the plate. The microcracks were deep enough to cause a critical fatigue crack to form and grow in the L-T direction. An SEM image of the critical crack origin on the fracture surface is shown in figure 21. An SEM image of the specimen corroded surface near the crack origin is shown in figure 22, and highlights the microcracks on the surface. This was the only test specimen that showed evidence of microcracking. The cause of the microcracking is unknown.

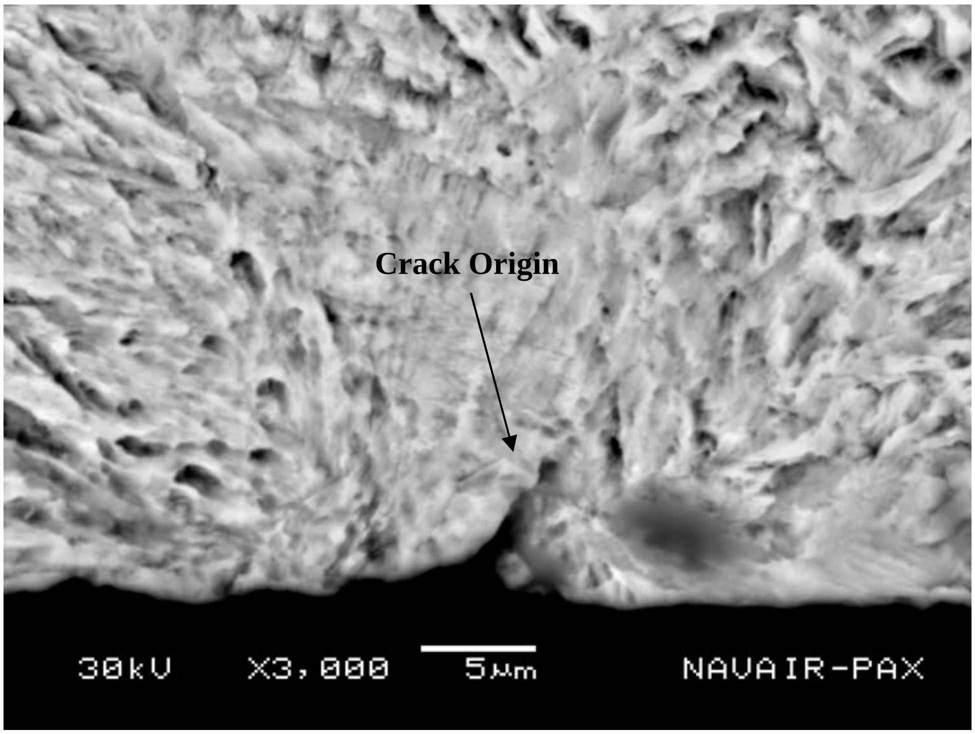

Figure 21: Fracture Surface SEM Image of Critical Crack Origin on Specimen 547-7B

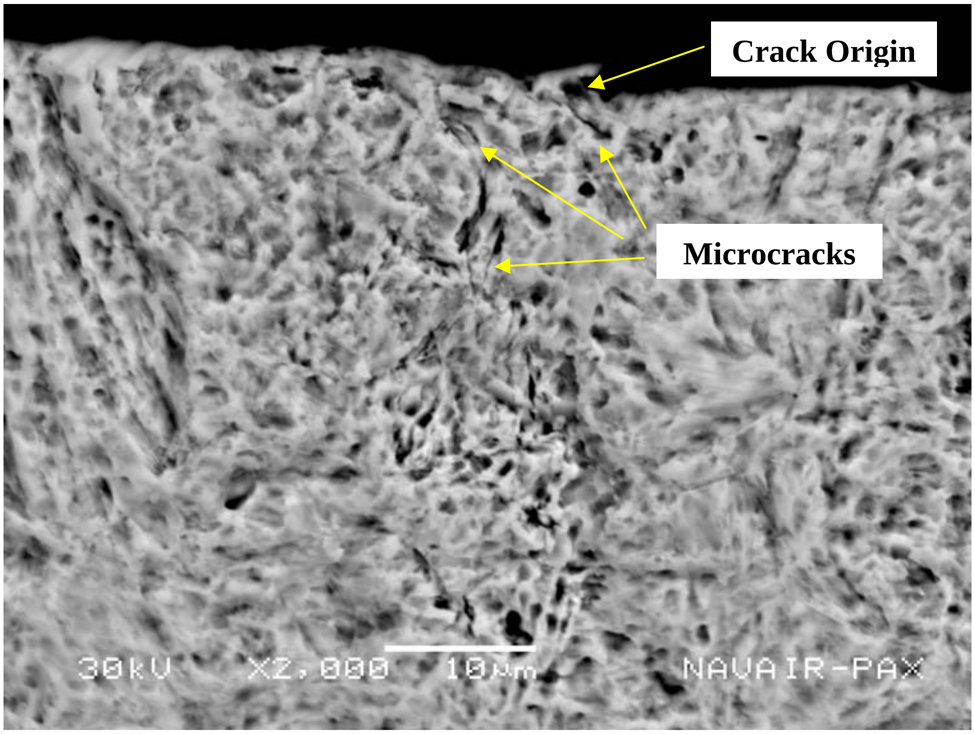

Figure 22: Corroded Surface SEM Image of Critical Crack Origin on Specimen 547-7B

CONCLUSIONS

The corrosion characteristic data and fatigue test results documented in this report can provide an excellent foundation for the development of metrics to characterize the severity of corrosion damage with respect to fatigue life reduction, and probabilistic models to predict the fatigue life reduction of corrosion-damaged airframe components. The test data set includes a robust and detailed characterization of the topology of surface corrosion damage on bare AF1410 steel material, allowing a quantitative assessment of corrosion severity to be performed, given that an appropriate model is developed.

Fracture toughness testing has shown that the billet of material used to fabricate all of the Batch B tests specimens was outside of specified material property allowables for AF1410 steel airframe components. However, additional testing indicated that the crack growth rate of this material is equivalent to the nominal crack growth rate of other batches of AF1410 material. Fractographic analysis of all of the corrosion-fatigue test specimens has shown that the critical cracks initiate from corrosion notches or longitudinal grinding gouges on the uncorroded portions of the surface, with one exception. Also, all the test plates failed well after crack initiation (0.010 in. crack depth) was reached. Therefore, it is reasonable to assume that the material anomalies present in the Batch B billet have little effect on the crack initiation life results reported here, and these anomalies should not affect the subsequent corrosion-fatigue models developed using this dataset. Use of this data to predict fatigue life behavior beyond crack initiation should be done with caution.

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REFERENCES

1. UDR-TR-2007-00039, “Navy High-Strength Steel Corrosion-Fatigue Modeling Program,” University of Dayton Research Institute, Dayton, OH, of Oct 2006.

2. ASTM E399, “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials,” ASTM International, West Conshohocken, PA.

3. ASTM E647, “Standard Test Method for Measurement of Fatigue Crack Growth Rates,” ASTM International, West Conshohocken, PA.

4. MMS214, “Steel Bars and Forgings, AF1410,” Boeing Material Specification, of 4 Apr 1980.

5. Laboratory Report MT1180, “Hardness Measurements on AF1410 Billet Section,” Aerospace Materials Division (AIR 4.3.4), NAVAIRSYSCOM, Patuxent River, MD, of 2 Feb 2005.

6. ASTM E8, “Standard Test Methods for Tension Testing of Metallic Materials,” ASTM International, West Conshohocken, PA.

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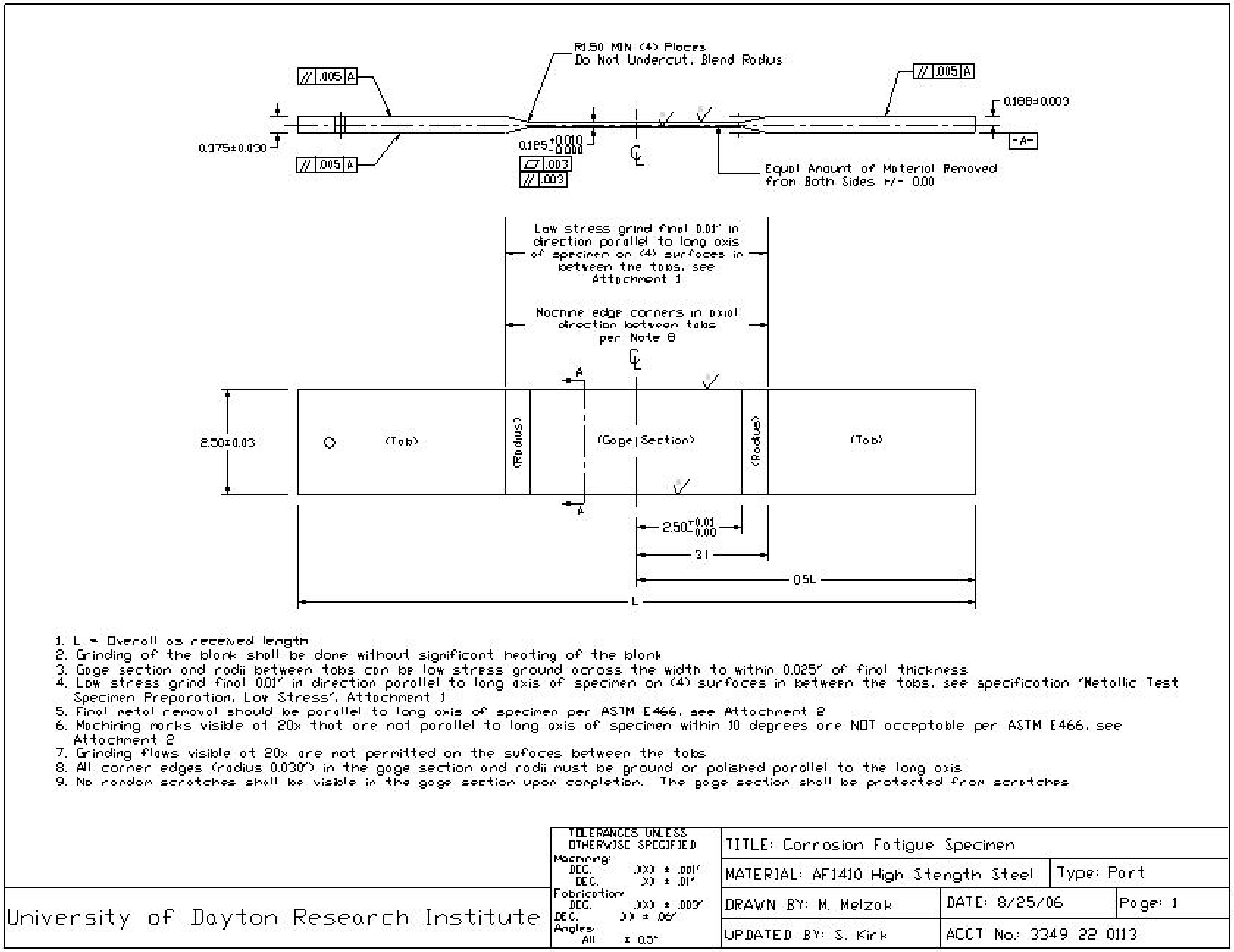
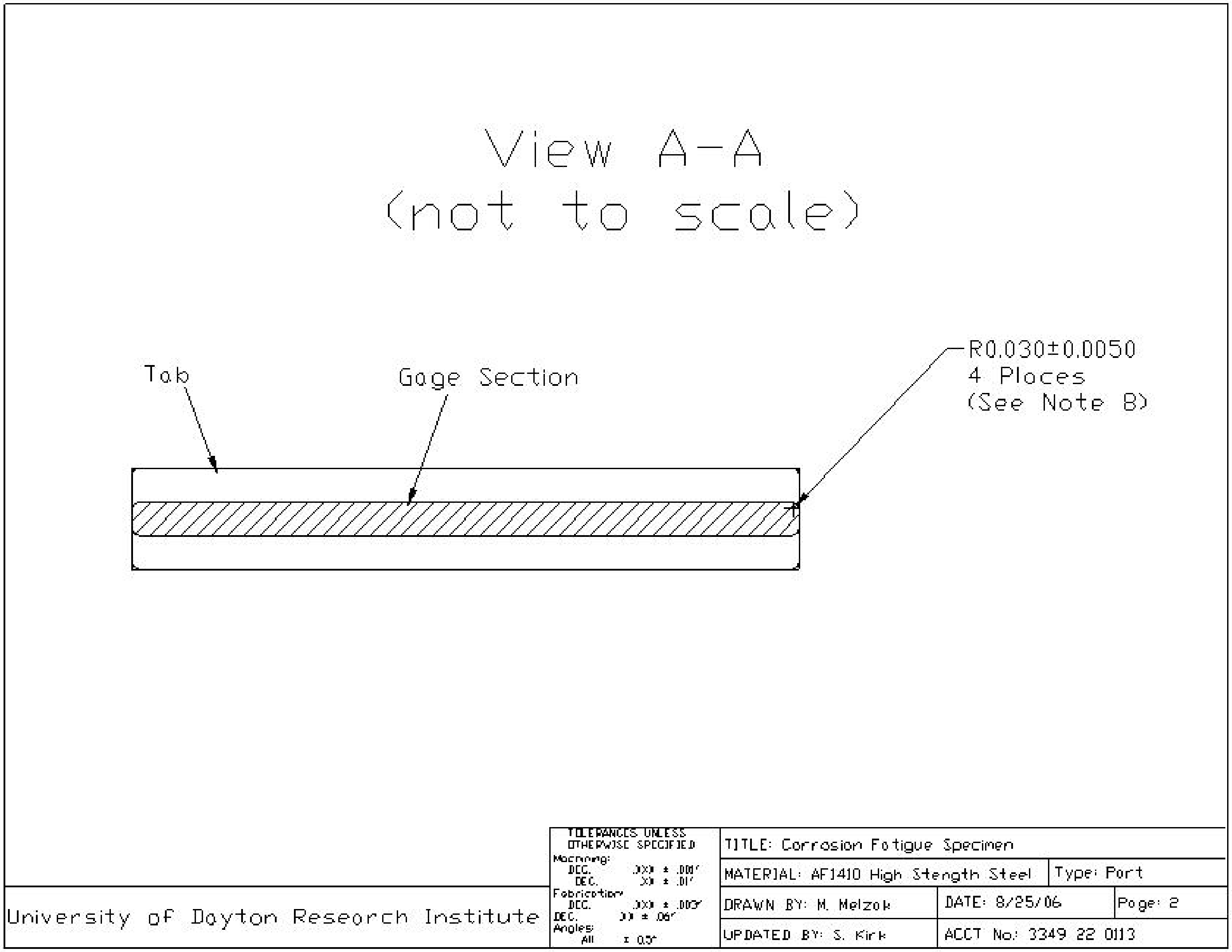
APPENDIX A
AF1410 BATCH B CORROSION FATIGUE TEST SPECIMEN DRAWINGS




View A-A
(not to scale)
Tab
Gage Section
R0.030±0.0050
4 Places
(See Note B)
University of Dayton Research Institute
TOLERANCES UNLESS OTHERWISE SPECIFIED
Machining:
Fabrication:
Angles:
TITLE: Corrosion Fatigue Specimen
MATERIAL: AF1410 High Stength Steel
Type: Part
DRAWN BY: M. Melzak
DATE: 8/25/06
Page: 2
UPDATED BY: S. Kirk
ACCT No: 3349 22 0113

APPENDIX B
RECOMMENDATIONS FOR HAND-POLISHING SPECIMENS FOR FATIGUE TESTING

The goals to be achieved by hand polishing these fatigue specimens are as follows:

a. Remove any machining markings and large anomalies that are transversely oriented to the loading direction from the specimens' gage and radii sections, which might influence the test results.

b. Keep the surface residual stresses low by minimizing pressure and heat generation during the final surface preparation. Our goal is to keep the residual stresses in the range called out by low stress, specimen preparation specifications we are following.

c. Achieve the appropriate surface finish called out by the low stress specimen preparation specifications we are following without creating a mirror finish.

GENERAL PROCEDURES

Follow the Low Stress metallic test specimen preparation procedures:

a. We used 180, 240, 320, and 400 grit SiC paper whereas the procedures call out for 240, 400, and 600 grit Al2O3 paper. This is to be decided.

Do's and Don'ts

a. Wipe the specimen with ethanol using a Kimwipe.

b. Find a flat surface to work and make sure your work surface is clean before you begin.

c. Secure your specimen down gently using a quick grip or other clamp such that you can work on the desired surface. Make sure the specimen is flat to the work surface and does not flex.

d. Use a piece of wood with a sharp corner to back your SiC or Al2O3 paper – cut a piece of paper to wrap around the wood block that is wider than the surface you are going to work on.

e. Start pushing the blocked paper longitudinally across the specimen away from you – start at the start of the tab and end at the start of the opposite tab. When starting and stopping, use a quick and smooth motion.

f. <u>Only go in one direction (longitudinally) – away from you</u>.

g. Use very little pressure – enough to feel a slight amount of resistance, especially with the largest grit paper. The specimen should not flex, especially in the thinner gage section. If you press too hard you will impart residual stresses in the surface which is what we are trying to avoid.

h. Clean the specimen off with a clean Kimwipe often, after every few strokes.

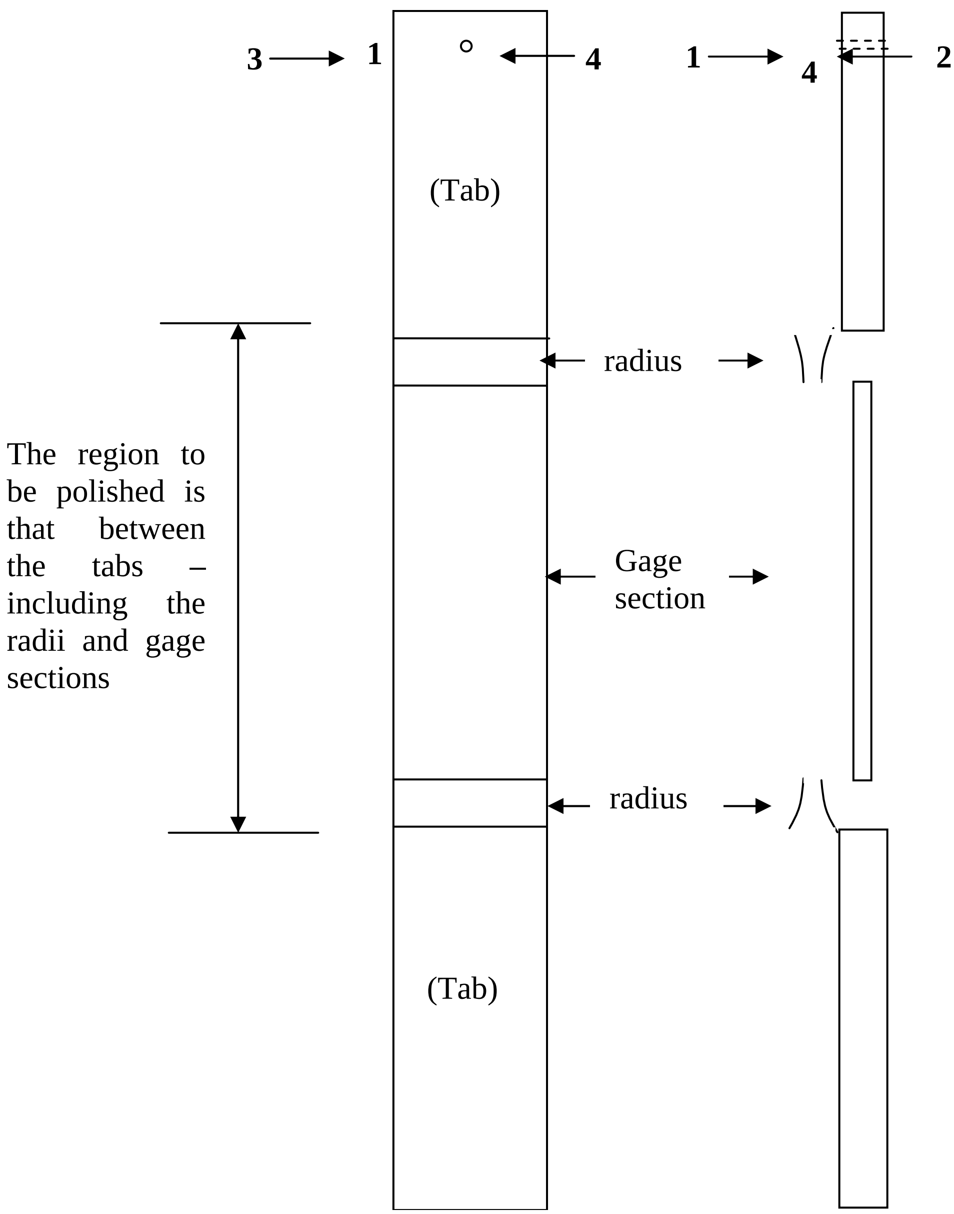
i. Polish with each finer grit paper until all longitudinal marks caused by the previous grit size paper are removed.

j. Between grit sizes, clean area entirely, wipe specimen with alcohol, and clean hands.

k. Do not grip block and paper too tightly – this will cause you discomfort. Do not press too hard – not good for you or your specimens. Take breaks often to rest.

<u>PROCEDURS FOR C-F SPECIMENS</u>

1. Number the four surfaces of the specimen in the tab area with a Sharpie marker. Put your label on the tab end that has the hole in it. Label the flat surfaces 1 and 2 and the edge surfaces 3 and 4.



2. Inspect your specimen on all surfaces at 50x (5x objective) to get an idea of what the damage on the surface looks like. Take note of scratches or other anomalies that are perpendicular to the long axis of the specimen. Pay particular attention to damage at the corners. These need to be removed along with deep features.

3. Start with 180 grit – We tended to work on the edges first (sides 3 and 4) and then worked on the big flat surfaces (sides 1 and 2). Sometimes one can slip when working on 3 and 4, which puts scratches on 1 and 2. So we would do 1 and 2 last for each grit.

   a. Start on surface 3. Set up specimen such that the end with the number 3 you wrote on the specimen is away from you.

(1) With your finger or the block backing the paper, start polishing the corners, with longitudinal strokes going away from you. Only go in the direction away from you.

(2) Start with the left corner and continue for 5 min using longitudinal strokes going away from you.

(3) Wipe the specimen often between strokes during that 5 min.

(4) You should probably average about 30 strokes per minute (?)

(5) Next polish the right corner and continue for 5 min using longitudinal strokes going away from you.

(6) Clean specimen with alcohol.

(7) With light pressure, start polishing surface number 3 using longitudinal strokes going away from you for a total of 5 min.

(8) Wipe the specimen often between strokes during that 5 min.

(9) You should probably average about 30 strokes per minute (?)

(10) After 5 min, unclamp specimen, wipe it and your area if necessary and rotate specimen such that the number 3 is closest to you.

(11) Repeat procedure such that each corner and the surface gets a total of 30 min.

(12) Clean specimen with alcohol and check surface number 3 and both corners (left and right) under the microscope and see if there are any marks that are not parallel to the long axis within the gage section.

(13) If there are, then repeat the entire process in the corners and on the edge labeled side 3. Repeat as necessary until all large anomalies and transverse marks are gone. Do not move on to another grit until all of the transverse marks are gone.

(14) If all transverse marks and large anomalies are gone, then stop using 180 on surface number 3. Clean the specimen with alcohol.

b. Start on surface 4. Set up specimen such that the end with the number 4 you wrote on the specimen is away from you.

(1) With your finger or the block backing the paper, start polishing the corners, with longitudinal strokes going away from you. Only go in the direction away from you.

(2) Start with the left corner and continue for 5 min using longitudinal strokes going away from you.

(3) Wipe the specimen often between strokes during that 5 min.

(4) You should probably average about 30 strokes per minute (?)

(5) Next polish the right corner and continue for 5 min using longitudinal strokes going away from you.

(6) Clean specimen with alcohol.

(7) With light pressure, start polishing surface number4 using longitudinal strokes going away from you for a total of 5 min.

(8) Wipe the specimen often between strokes during that 5 min.

(9) You should probably average about 30 strokes per minute (?)

(10) After 5 min, unclamp specimen, wipe it and your area if necessary and rotate specimen such that the number 4 is closest to you.

(11) Repeat procedure such that each corner and the surface gets a total of 30 min.

(12) Clean specimen with alcohol and check surface number 4 and both corners (left and right) under the microscope and see if there are any marks that are not parallel to the long axis within the gage section.

(13) If there are, then repeat the entire process in the corners and on the edge labeled side 4. Repeat as necessary until all large anomalies and transverse marks are gone. Do not move on to another grit until all of the transverse marks are gone.

(14) If all transverse marks and large anomalies are gone, then stop using 180 on surface number 4. Clean the specimen with alcohol.

c. Start on surface 1. Set up specimen such that the tab end with the number 1 you wrote on the specimen is away from you.

(1) With light pressure, start polishing using longitudinal strokes going in the direction away from you only for a total of 5 min.

(2) Wipe the specimen often between strokes during that 5 min.

(3) You should probably average about 30 strokes per minute (?)

(4) After 5 min, unclamp specimen, wipe it and your area if necessary and rotate specimen such that the number 1 is closest to you.

(5) Repeat this process rotating the specimen every 5 min until you have a total time on the specimen of 20 min.

(6) Clean specimen with alcohol and check surface number1 under the microscope and see if there are any marks that are not parallel to the long axis within the gage section.

(7) If there are, then continue process for 20 more minutes and recheck. If still there are nonparallel marks, then continue for 20 more minutes, and repeat as necessary until all large anomalies and transverse marks are gone. Do not move on to another grit until all of the transverse marks are gone.

(8) If all transverse marks and large anomalies are gone, then stop using 180 on surface number1. Clean the specimen with alcohol.

d. Start on surface 2. Set up specimen such that the end with the number 2 you wrote on the specimen is away from you.

(1) With light pressure, start polishing using longitudinal strokes going in the direction away from you only for a total of 5 min.

(2) Wipe the specimen often between strokes during that 5 min.

(3) You should probably average about 30 strokes per minute (?)

(4) After 5 min, unclamp specimen, wipe it and your area if necessary and rotate specimen such that the number 2 is closest to you.

(5) Repeat this process rotating the specimen every 5 min until you have a total time on the specimen of 20 min.

(6) Clean specimen with alcohol and check surface number 2 under the microscope and see if there are any marks that are not parallel to the long axis within the gage section.

(7) If there are, then continue process for 20 more minutes and recheck. If still there are nonparallel marks, then continue for 20 more minutes, and repeat as necessary until all large anomalies and transverse marks are gone. Do not move on to another grit until all of the transverse marks are gone.

(8) If all transverse marks and large anomalies are gone, then stop using 180 on surface number 2. Clean the specimen with alcohol.

REPEAT PROCEDURES USING PROGRESSIVELY SMALLER GRIT SIZES WITH THE 5-MIN ROTATIONS SUCH TO ACHIEVE THE MAXIMUM TIMES IN THE CHART BELOW:

Name:			**Specimen:**			**Date:**			
SiC Paper	**LC3**	**S3**	**RC3**	**LC4**	**S4**	**RC4**	**S1**	**S2**	
(grit)	**(10 min)**	**(10 min)**	**(10 min)**	**(10 min)**	**(10 min)**	**(10 min)**	**(20 min)**	**(20 min)**	
180	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓ 5↑ 5↓	5↑ 5↓ 5↑ 5↓	**1 hr + 40 min**
240	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓ 5↑ 5↓	5↑ 5↓ 5↑ 5↓	**1 hr + 40 min**
320	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓ 5↑ 5↓	5↑ 5↓ 5↑ 5↓	**1 hr + 40 min**
400	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓	5↑ 5↓ 5↑ 5↓	5↑ 5↓ 5↑ 5↓	**1 hr + 40 min**
								total	**6 hr + 40 min**

LC3 = left corner side 3
S3 = the small flat of side 3
RC3 = right corner side 3

LC4 = left corner side 4
S4 = the small flat of side 4
RC4 = right corner side 4

S1 = big flat surface – side 1
S2 = big flat surface – side 2

APPENDIX C
AF1410 BATCH B C-F SPECIMEN RESIDUAL STRESS MEASUREMENTS

Table C-1: Residual Stress Depth Measurements

Lambda Research, Inc.

13281.d01 STRESS 40.20 2/1/2007

RESIDUAL STRESS DEPTH ANALYSIS
With Stress Gradient and Relaxation Corrections
and Diffraction Peak Width (B 1/2)

A1410 STEEL LSG SAMPLE LONGITUDINAL DIRECTION
Specimen 547-18C Mid-Gage Location

E/(1+v) = 24500. ± 441. ksi   1/2 S2 = 5.92 ± .11 x 10-6 1/MPa
MU= 2307. 1/in. (90.8 1/mm)   Sectioning Stress Relax. = .0 ksi

	DEPTH	**RESIDUAL STRESS ksi (MPa)**			**B 1/2**
	in. (mm)	MEASURED	GRADIENT	RELAXATION	(deg)
1	0.0000 (0.0000)	-60.9 ± 2.6 (-420 ± 18)	-92.3 (-636)	-92.3 (-636)	3.71
2	0.0006 (0.0152)	-3.8 ± 1.5 (-26 ± 11)	-11.0 (-76)	-10.0 (-69)	3.49
3	0.0010 (0.0254)	-5.1 ± 1.6 (-35 ± 11)	-4.8 (-33)	-3.7 (-25)	3.47
4	0.0020 (0.0508)	-3.5 ± 1.5 (-24 ± 11)	-3.3 (-23)	-2.1 (-14)	3.51
5	0.0033 (0.0838)	-5.8 ± 1.6 (-40 ± 11)	-5.1 (-35)	-3.7 (-26)	3.51

Specimen 614-20 Mid-Gage Location

	DEPTH	**RESIDUAL STRESS ksi (MPa)**			**B 1/2**
	in. (mm)	MEASURED	GRADIENT	RELAXATION	(deg)
1	0.0000 (0.0000)	-34.7 ± 2.2 (-239 ± 15)	-54.5 (-376)	-54.5 (-376)	3.52
2	0.0005 (0.0127)	-5.2 ± 1.6 (-36 ± 11)	-11.7 (-80)	-11.1 (-76)	3.47
3	0.0010 (0.0254)	-5.5 ± 1.6 (-38 ± 11)	-5.6 (-38)	-4.8 (-33)	3.50
4	0.0020 (0.0508)	-4.0 ± 1.6 (-28 ± 11)	-4.1 (-28)	-3.2 (-22)	3.48
5	0.0031 (0.0787)	-5.0 ± 1.6 (-35 ± 11)	-4.7 (-33)	-3.7 (-25)	3.46

Specimen 614-26 Mid-Gage Location

1	0.0000 (0.0000)	-72.8 ± 2.9 (-502 ± 20)	-110.2 (-759)	-110.2 (-759)	3.68
2	0.0006 (0.0152)	0.7 ± 1.4 (5 ± 10)	-10.4 (-71)	-9.1 (-63)	3.52
3	0.0011 (0.0279)	2.0 ± 1.4 (14 ± 10)	1.7 (12)	3.0 (21)	3.50
4	0.0019 (0.0483)	1.3 ± 1.4 (9 ± 10)	1.4 (10)	2.6 (18)	3.50
5	0.0033 (0.0838)	0.6 ± 1.4 (4 ± 10)	0.6 (4)	1.7 (12)	3.52

Table C-2: Surface Residual Stress, Center of Gage Section

Lambda Technologies 396-13281
SURFACE LONGITUDINAL RESIDUAL STRESSES
AF1410 Steel LSG Samples
Mid-Gage Location

SPECIMEN	RESIDUAL STRESS (ksi)	RESIDUAL STRESS (MPa)	PEAK WIDTH (deg.)
598-11	-118.2 ± 3.7	-815 ± 26	3.48
598-14	-101.5 ± 3.3	-700 ± 23	3.53
598-15	-107.9 ± 3.6	-744 ± 25	3.66
547-40B	-83.8 ± 3.2	-578 ± 22	3.79
614-26	-72.8 ± 2.9	-502 ± 20	3.68
614-20	-34.7 ± 2.2	-239 ± 15	3.52
547-18C	-60.9 ± 2.6	-420 ± 18	3.71

Table C-3: Surface Residual Stress, Two Locations of Gage Section

Lambda Technologies 396-13281
SURFACE LONGITUDINAL RESIDUAL STRESSES
AF1410 Steel LSG Samples

SPECIMEN	LOCATION	RESIDUAL STRESS (ksi)	RESIDUAL STRESS (MPa)	PEAK WIDTH (deg.)
545-1C	A	-102.0 ± 3.4	-703 ± 23	3.51
	B	-103.5 ± 3.4	-714 ± 24	3.45
614-9	A	-89.3 ± 3.2	-616 ± 22	3.73
	B	-88.5 ± 3.2	-610 ± 22	3.79
614-23	A	-28.6 ± 2.1	-197 ± 14	3.66
	B	-31.9 ± 2.2	-220 ± 15	3.55

APPENDIX D
PROCEDURES FOR CORROSION EXPOSURE OF AF1410 FATIGUE TEST SPECIMENS WITH AN APPROXIMATE 1-INCH DIAMETER CORROSION AREA USING PROGRESSIVELY LARGER FILTER PAPER CIRCLES

Read all steps before beginning.

1. Only expose one specimen at a time – these procedures pertain to the setup for corrosion exposure of one corrosion-fatigue specimen. We will not expose more than one specimen at a time.

2. Use gloves when handling specimens – especially after they have been cleaned.

3. Take photo of both surfaces of specimen in the “as received” condition for our records.

4. Enhance the existing number on the specimen with the scribe if necessary

5. Clean specimens to remove oil.

    a. In plastic container, clean by hand test specimen in mixture of light soap and tap water.

    b. Rinse with the tap water.

    c. Rinse corrosion area with solvent that will not leave residue (ethyl alcohol) and wipe dry with Kimwipe.

6. Start a new entry in the notebook for the test specimen and date if have not already.

7. Spot-weld Nichrome wire to edge of the specimen opposite the ID number (bottom).

8. Weigh the cleaned, uncorroded, specimen using the triple-beam balance scale (The digital scale will not accommodate the weight of the corrosion-fatigue specimens ~1550g). Record measurement in the notebook.

9. Carefully mark the approximate location for the first or smallest filter paper size as well as for the largest filter paper to be used – the filter paper should be centered in the gage section of the test specimen. The first filter paper size is approximately 0.875 in. in diameter. Use a soft, permanent, felt tipped pen or marker to mark the specimen – DO NOT USE PENCIL. Do not put marks inside where the first corrosion exposure will be. Mark the 12, 3, 6, and 9 o’clock positions outside the 0.875 in. diameter to approximately line up where the filter paper shall be placed.

10. Take photo of both surfaces of clean specimen (make sure there is a label and scale in photo – make sure we know which end has specimen number as well).

11. Mix reagent grade salt solution that is 3.5% concentrated by weight. Mix and use new solution as often as daily – the same solution may be used for more than 1 day on the same specimen up to 2 days. (Use deionized water from Jeff Sturgill's lab.) Store solution in a container with lid or cover and label the container with the mix date. It is important to avoid contamination and evaporation.

12. Cut circles of filter paper that are 0.875, 0.9375, 1, and 1.0625 in. and soak in salt solution – make sure paper is soaked for some minimum length of time to insure it is completely soaked. Only put one size filter paper in solution at a time so that they will not be used incorrectly by mistake. Consult with the test matrix/work request for how many of each sized circles are needed and when to use them.

13. Place the specimen on the test stand with the "top" surface facing up, i.e., the surface to be corroded facing up. The top surface is the surface such that the scribed specimen number reads correctly. Currently, we propose to consistently corrode the top surface.

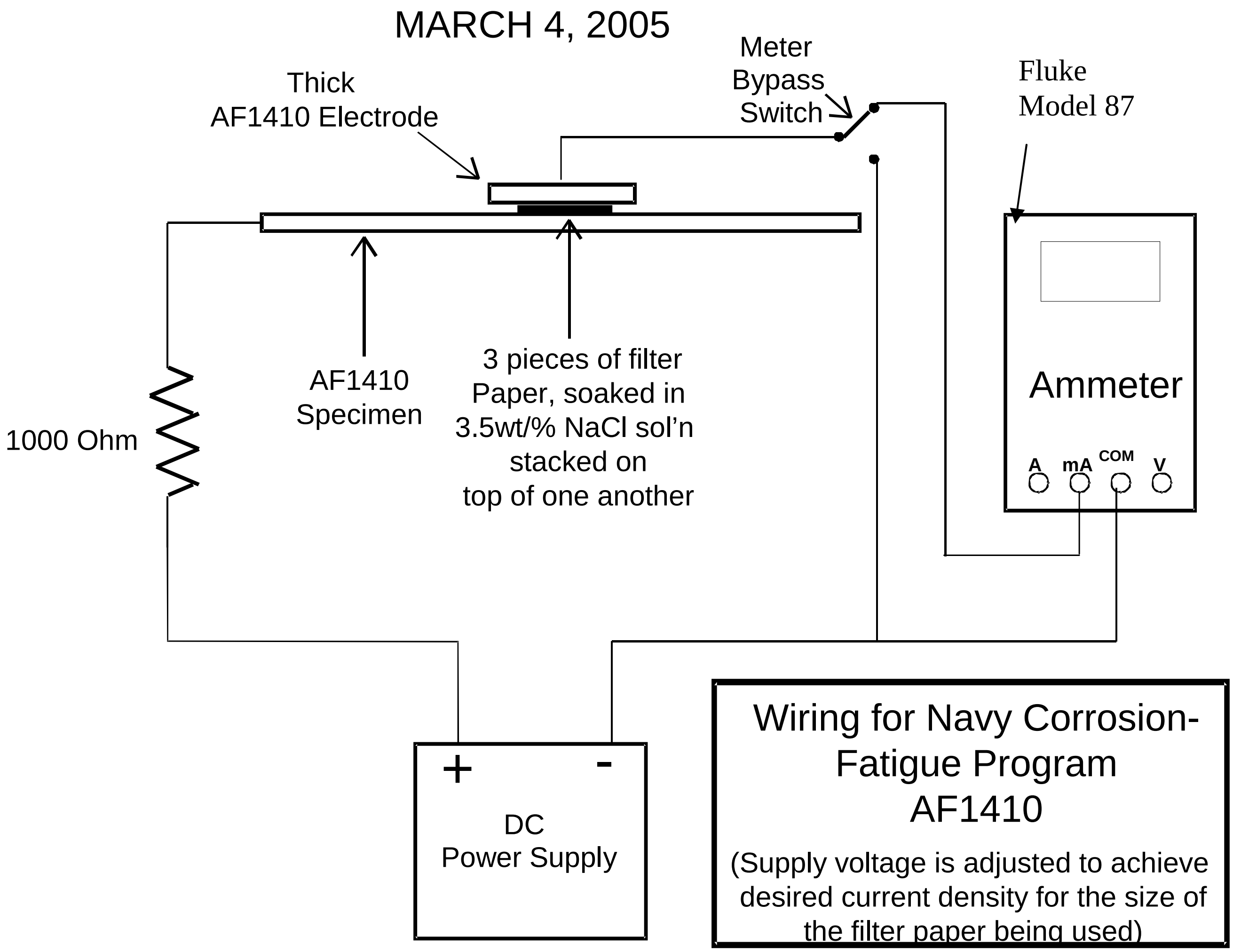
14. Make sure the specimen is sitting level – Check with a level and use shim under the stand as necessary. This is to keep water that may wick out from going from one side or the other and also to help ensure that the electrode sitting on top will not lean and short out.

15. Make sure circuit is properly instrumented as in the following schematic and that all bare wires are constrained to prevent touching. Make sure the multimeter (Fluke Model 87) used to read current in the circuit has working batteries and that it is functioning properly. Make sure the "thick piece" of AF1410 that is designated as the top electrode instrumented properly. In this configuration, when the multimeter is turned "off", it will add unwanted resistance to the circuit. The meter bypass switch should always be in the "bypass" position before turning the meter on or off or letting it turn off automatically.

NOTE:

The Fluke Model 87 will turn off automatically after approximately 15 min.

Before turning the power supply or the multimeter on or off, or letting the multimeter turn off automatically, for any of the steps in this procedure, make sure the meter bypass switch is set to "bypass".



16. Expose the specimen for the proper times and current readings (consult test matrix/ work request). Record the date, start and end times, and current reading for each cycle in the notebook.

NOTE:
Use the following test parameters for the 1.5-hr, 3-hr, 6-hr, and 12-hr exposures, respectively.

1.5-hr Exposure

Cycle	Exp Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.9375	8.79	8.79	~12.74
5	35	55	1	10	10	~12.74
6	35	90	1.0625	11.29	11.29	~12.74

3-hr Exposure

Cycle	Exp Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.875	7.66	7.66	~12.74
5	40	60	0.9375	8.79	8.79	~12.74
6	60	120	1	10	10	~12.74
7	60	180	1.0625	11.29	11.29	~12.74

6-hr Exposure

Cycle	Exp Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.875	7.66	7.66	~12.74
5	40	60	0.875	7.66	7.66	~12.74
6	60	120	0.9375	8.79	8.79	~12.74
7	120	240	1	10	10	~12.74
8	120	360	1.0625	11.29	11.29	~12.74

12-hr Exposure

Cycle	Exp Time (min)	Total Time (min)	Diameter (in.)	Voltage (V)	Current (mA)	Current Density (mA/in.^{2})
1	1	1	0.875	7.66	7.66	~12.74
2	1	2	0.875	7.66	7.66	~12.74
3	8	10	0.875	7.66	7.66	~12.74
4	10	20	0.875	7.66	7.66	~12.74
5	40	60	0.875	7.66	7.66	~12.74
6	60	120	0.875	7.66	7.66	~12.74
7	60	180	0.875	7.66	7.66	~12.74
8	60	240	0.9375	8.79	8.79	~12.74
9	120	360	0.9375	8.79	8.79	~12.74
10	120	480	1	10	10	~12.74
11	60	540	1	10	10	~12.74
12	60	600	1.0625	11.29	11.29	~12.74
13	120	720	1.0625	11.29	11.29	~12.74

17. Apply a stack of three pieces of appropriately sized filter paper that are as precisely aligned to each other as possible onto the specimen in the proper location.

    a. Take a single piece of filter paper out of solution with the Teflon tweezers and lay on clean paper towel.

    b. Take second piece out, line it up, and lay it on top of first piece.

    c. Take third piece out, line it up, and lay it on top of second piece.

    d. When three are stacked, pick up with tweezers and submerge in the salt solution for at least 5 sec.

    e. Set filter paper stack on new paper towel (let go with the tweezers) for 1 sec.

    f. Pick up filter paper stack and turn over on dry place of paper towel (let go with the tweezers) for 1 sec.

    g. Immediately pick up stack and place in the center of test specimen.

18. Carefully apply the “thick piece” of AF1410 that has been designated as the top electrode and the glass shield.

19. Ensure that the meter bypass switch in the circuit is set to “bypass”.

20. Turn on power supply, then quickly turn on the multimeter to mA, and then flip the meter bypass switch to “meter”. **Set the proper current** by increasing the voltage until the multimeter reads the appropriate current to achieve a current density of 12.74 $mA/in.^2$. Consult with the test matrix/work request for the appropriate settings. With configuration shown above, double check that the voltage setting is *approximately* equal to the current (if way off, turn off the power supply and double check setup – something may be wrong). Record the current reading in the notebook for the cycle being performed. After the current is recorded, the multimeter can be shut off to preserve the batteries. The proper procedure for shutting off the multimeter is to first, flip the meter bypass switch to the “bypass” position and then turn the multimeter off.

NOTE:
The Fluke Model 87 will turn off automatically after approximately 15 min – the proper shutdown procedure is to set the switch to “bypass” first before the meter is shut off.

21. After each cycle, shut off power supply, remove top electrode and wipe it dry. Wipe electrode with ethyl alcohol between cycles.

22. Remove filter paper and wipe specimen surface dry (no ethyl alcohol) – make sure it is completely dry by wiping or using canned air.

23. Take photos of corroded specimen surface with the camera – one picture capturing the corroded area. (put label and scale in photo as needed).

24. Write notes as needed regarding filter paper appearance, specimen surface, testing observations, etc.

25. Start next cycle or store specimen in sealable bag with a desiccant.

26. After specimen corrosion exposure is completed:

    a. Weigh the corroded but uncleaned specimen using the triple-beam balance scale (The digital scale will not accommodate the weight of the corrosion-fatigue specimens ~1550g). Record measurement in the notebook.

    b. Clean the specimen and top electrode using the Boeing Spec / UDRI’s procedures:
        - Mix new ~ 75 vol% conc. TURCO in tap water.
        - Heat until solution is ~ 190°F.
        - Place stainless steel wire hook through the hole in the specimen in place in tank.
        - Submerge for ~ 10 min and then remove into a pan of tap water.
        - Remove from tap water, rub with gloved hands using soap and water, and rinse thoroughly.
        - Dry completely with paper towel.
        - If not clean, put back into heated TURCO for ~ 5 min and repeat.
        - When clean of corrosion by-products, clean ultrasonically in ethyl alcohol for 30 sec.
        - Dry with Kimwipes and, for approximately 5 min, with a heat gun.

    c. Weigh the corroded but cleaned specimen using the triple-beam balance scale (The digital scale will not accommodate the weight of the corrosion-fatigue specimens ~1550g). Record measurement in the notebook.

    d. Scrape off nichrome wire.

    e. Take photos of corroded specimen surface with the camera – one picture capturing the corroded area (put label and scale in photo as needed).

    f. Carefully, scan in and save two images of the specimen surface on one of the lab’s scanners if it is not too heavy for the scanner bed. Use small pieces of bubble wrap at the specimen ends to protect the scanner. Be careful not to scratch the glass. In one image, capture both tab edges lengthwise and the specimen width in the other direction. In the second image, capture the corroded area only but make sure the

edges of the specimen (widthwise) are in the image. When loading into the scanner, always put the end with the hole in the specimen toward the scanner lid hinge.

27. Store exposed specimen by wrapping in a Kimwipe and store in a plastic bag with a desiccant.

28. Give corroded test specimen to Doug Wolf to obtain mechanical stylus profilometry of the corroded area and the interfaces.

29. Give corroded test specimen to Eric Burke to obtain a replica of the surface and WLI measurements.

30. Wrap stored exposed specimen in bubble wrap and pack in designated crate for shipping.

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APPENDIX E
AF1410 BATCH B FATIGUE CRACK GROWTH RATE TESTS

Table E-1: FCGR Test Results for Specimen STL614-30, R = 0.1 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
4.38E-07	10.31977	2.01E-06	14.50834	5.28E-06	20.7045	1.39E-05	32.67425
4.5E-07	10.50804	2.06E-06	14.69865	5.44E-06	21.03276	1.48E-05	33.7834
4.65E-07	10.6429	2.15E-06	14.88686	5.65E-06	21.41326	1.55E-05	34.53461
4.83E-07	10.76407	2.2E-06	15.13953	5.89E-06	21.73821	1.58E-05	35.24883
5.84E-07	10.95934	2.29E-06	15.32515	6.11E-06	22.07205	1.61E-05	36.14164
6.66E-07	11.11959	2.48E-06	15.51401	6.35E-06	22.4835	1.67E-05	36.99647
7.71E-07	11.2512	2.57E-06	15.73807	6.64E-06	22.81809	1.78E-05	37.80325
8.83E-07	11.39243	2.63E-06	15.91542	7.04E-06	23.17783	1.89E-05	38.60261
9.63E-07	11.58341	2.72E-06	16.16134	7.24E-06	23.57591	1.98E-05	39.59524
9.87E-07	11.76792	2.81E-06	16.35997	7.53E-06	23.96142	2.05E-05	40.63884
1.04E-06	11.87841	2.97E-06	16.60167	7.75E-06	24.47912	2.18E-05	41.594
1.11E-06	12.10788	3.09E-06	16.86552	8.12E-06	24.8367	2.3E-05	42.54316
1.16E-06	12.21306	3.21E-06	17.08325	8.37E-06	25.3114	2.43E-05	43.62203
1.18E-06	12.37093	3.33E-06	17.33517	8.73E-06	25.80109	2.55E-05	45.27648
1.25E-06	12.5662	3.52E-06	17.59286	8.91E-06	26.27733	2.68E-05	46.4841
1.28E-06	12.71069	3.67E-06	17.87997	9.11E-06	26.8513	2.83E-05	47.67436
1.33E-06	12.86151	3.76E-06	18.1005	9.38E-06	27.28019	3.09E-05	48.877
1.4E-06	13.07535	3.81E-06	18.39493	9.98E-06	27.77942	3.32E-05	50.65888
1.45E-06	13.25247	3.94E-06	18.67782	1.05E-05	28.29518	3.56E-05	52.04377
1.52E-06	13.40995	4.1E-06	18.85476	1.1E-05	28.85768	3.75E-05	53.68436
1.59E-06	13.59699	4.32E-06	19.21699	1.13E-05	29.52926		
1.66E-06	13.71726	4.63E-06	19.42401	1.19E-05	30.0414		
1.73E-06	13.91821	4.85E-06	19.82284	1.24E-05	30.79097		
1.8E-06	14.12254	4.98E-06	20.04236	1.29E-05	31.34392		
1.94E-06	14.32111	5.1E-06	20.41377	1.34E-05	32.08129		

Table E-2: FCGR Test Results for Specimen STL614-31, R = 0.1 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
1.61E-07	6.451276	5.29E-07	9.505064	1.97E-06	14.54117	9.38E-06	25.99975
1.86E-07	6.618925	4.81E-07	9.554054	2.1E-06	14.79537	9.72E-06	26.90503
1.93E-07	6.670296	4.8E-07	9.681223	2.24E-06	15.10186	1.03E-05	27.51186
1.97E-07	6.786688	4.83E-07	9.873589	2.34E-06	15.50848	1.07E-05	28.26394
1.98E-07	6.878739	5.12E-07	10.0722	2.54E-06	15.73237	1.1E-05	29.23227
2.05E-07	7.016707	5.47E-07	10.25089	2.77E-06	16.02542	1.18E-05	29.89523
2.26E-07	7.098348	6.12E-07	10.41436	2.97E-06	16.36025	1.21E-05	31.00531
2.28E-07	7.148908	6.28E-07	10.57408	3.12E-06	16.75706	1.22E-05	32.11372
2.29E-07	7.274065	6.63E-07	10.73791	3.2E-06	17.10322	1.28E-05	32.16794
2.31E-07	7.359114	7.32E-07	10.95643	3.26E-06	17.64604	1.38E-05	32.60889
2.51E-07	7.502662	8.25E-07	11.09604	3.41E-06	17.93434	1.46E-05	33.50156
2.58E-07	7.590974	8.32E-07	11.27367	3.67E-06	18.33866	1.59E-05	34.77513
2.72E-07	7.690339	8.84E-07	11.48742	3.78E-06	18.5676	1.71E-05	35.98335
2.77E-07	7.78153	9.15E-07	11.77151	4.13E-06	18.7589	1.81E-05	37.11723
2.84E-07	7.904435	9.53E-07	12.01949	4.35E-06	18.95315	1.95E-05	38.53316
2.94E-07	8.024437	1.02E-06	12.29262	4.66E-06	19.35815	2.1E-05	39.88328
3.04E-07	8.131186	1.11E-06	12.46137	5E-06	19.89282	2.22E-05	41.641
3.18E-07	8.245363	1.17E-06	12.68734	5.32E-06	20.17733	2.37E-05	43.59641
3.33E-07	8.29792	1.24E-06	12.8221	5.58E-06	20.8159	2.58E-05	45.07829
4.25E-07	8.474796	1.29E-06	13.11078	5.92E-06	21.48326		
3.67E-07	8.612247	1.37E-06	13.25604	6.26E-06	21.88701		
3.59E-07	8.752692	1.48E-06	13.52314	6.72E-06	22.60939		
3.33E-07	8.905229	1.59E-06	13.71946	7.21E-06	23.1582		
3.52E-07	9.134143	1.72E-06	14.08338	7.74E-06	23.63974		
4.04E-07	9.160712	1.86E-06	14.29498	8.22E-06	24.18816		

Table E-3: FCGR Test Results for Specimen STL614-32, R = 0.1 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
3.17E-07	9.604701	1.66E-06	13.55908	4.73E-06	19.51756	1.33E-05	31.67399
3.55E-07	9.824784	1.68E-06	13.70748	4.94E-06	19.89212	1.38E-05	32.40241
4.18E-07	9.807224	1.76E-06	13.88341	5.21E-06	20.19191	1.48E-05	33.28852
5.82E-07	10.00139	1.8E-06	14.09493	5.5E-06	20.53053	1.56E-05	34.08619
5.84E-07	10.1519	1.86E-06	14.30116	5.85E-06	20.90295	1.61E-05	34.78831
6.15E-07	10.25023	2.04E-06	14.48805	6.05E-06	21.30463	1.67E-05	35.783
6.39E-07	10.42479	2.12E-06	14.69551	6.11E-06	21.69406	1.73E-05	36.68747
6.57E-07	10.67873	2.17E-06	14.93132	6.08E-06	22.0958	1.84E-05	37.62018
7.19E-07	10.79979	2.26E-06	15.13063	6.38E-06	22.43287	1.95E-05	38.46614
8.19E-07	10.98453	2.39E-06	15.31659	6.72E-06	22.91781	2.04E-05	39.81484
8.37E-07	11.08301	2.52E-06	15.54913	7.13E-06	23.33797	2.16E-05	40.80157
8.88E-07	11.23346	2.62E-06	15.76873	7.55E-06	23.65234	2.28E-05	42.07658
9.15E-07	11.38578	2.73E-06	16.01152	7.77E-06	24.20872	2.4E-05	43.04551
9.38E-07	11.56653	2.89E-06	16.23426	8.12E-06	24.63804	2.55E-05	44.29141
1.01E-06	11.75594	3.07E-06	16.51894	8.6E-06	25.20679	2.68E-05	45.85518
1.05E-06	11.85328	3.18E-06	16.70268	8.9E-06	25.70164	2.9E-05	47.15774
1.07E-06	11.99253	3.31E-06	16.9418	9.21E-06	26.08866	3.12E-05	48.45793
1.14E-06	12.16922	3.31E-06	17.22641	9.56E-06	26.73486	3.33E-05	50.13079
1.19E-06	12.37699	3.41E-06	17.50532	9.85E-06	27.22031		
1.26E-06	12.49447	3.58E-06	17.74355	1.04E-05	27.71714		
1.32E-06	12.68575	3.85E-06	18.02933	1.09E-05	28.33495		
1.37E-06	12.81515	4.02E-06	18.3297	1.13E-05	28.94191		
1.42E-06	13.02922	4.28E-06	18.63801	1.21E-05	29.56903		
1.47E-06	13.14812	4.45E-06	18.93288	1.25E-05	30.32379		
1.59E-06	13.35171	4.58E-06	19.16946	1.28E-05	30.96187		

Table E-4: FCGR Test Results for Specimen STL614-33, R = 0.5 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
5.72E-07	7.763192	1.03E-06	10.24159	2.7E-06	13.56357	6.33E-06	18.66472
4.58E-07	7.821866	1.04E-06	10.3211	2.73E-06	13.64203	6.3E-06	18.84567
4.67E-07	7.880747	1.09E-06	10.37387	2.91E-06	13.75762	6.22E-06	19.00448
4.21E-07	7.945224	1.11E-06	10.4545	2.96E-06	13.85629	6.33E-06	19.19954
4.34E-07	8.020532	1.14E-06	10.49419	2.99E-06	13.93766	6.54E-06	19.37206
4.81E-07	8.080191	1.16E-06	10.59666	3.01E-06	14.08573	6.59E-06	19.60321
5.39E-07	8.129359	1.23E-06	10.67201	3.15E-06	14.17968	7.05E-06	19.69911
5.32E-07	8.205544	1.25E-06	10.7269	3.23E-06	14.30207	7.38E-06	19.90587
5.43E-07	8.227865	1.25E-06	10.76788	3.36E-06	14.38798	7.48E-06	20.08942
5.49E-07	8.29925	1.28E-06	10.88777	3.38E-06	14.50784	7.51E-06	20.29469
5.45E-07	8.371057	1.3E-06	10.95114	3.37E-06	14.60356	7.39E-06	20.47197
5.64E-07	8.437718	1.4E-06	11.03692	3.42E-06	14.75437	7.34E-06	20.63742
5.65E-07	8.454432	1.53E-06	11.10883	3.63E-06	14.84185	7.92E-06	20.89289
5.67E-07	8.549649	1.8E-06	11.15186	3.64E-06	14.95664	8.26E-06	21.06445
6.16E-07	8.583274	1.57E-06	11.26177	3.64E-06	15.10932	8.36E-06	21.23404
6.33E-07	8.651096	1.54E-06	11.31306	3.67E-06	15.21544	8.35E-06	21.46022
6.27E-07	8.71932	1.43E-06	11.4248	3.65E-06	15.34319	8.26E-06	21.69054
6.37E-07	8.758962	1.48E-06	11.54546	3.69E-06	15.41673	8.37E-06	21.87457
6.44E-07	8.84522	1.55E-06	11.637	4E-06	15.59716	8.7E-06	22.15444
6.41E-07	8.891149	1.64E-06	11.69087	4.12E-06	15.67664	9.03E-06	22.4047
6.78E-07	8.960822	1.74E-06	11.81509	4.2E-06	15.77789	9.56E-06	22.53474
7.01E-07	8.995279	1.84E-06	11.89369	4.25E-06	15.93489	9.72E-06	22.7976
7.04E-07	9.041684	1.85E-06	11.92573	4.26E-06	16.05181	9.85E-06	22.99901
6.92E-07	9.130244	1.86E-06	12.04522	4.29E-06	16.15759	9.83E-06	23.25329
6.91E-07	9.219519	1.98E-06	12.11812	4.42E-06	16.35451	9.94E-06	23.58527
7.07E-07	9.242469	2.08E-06	12.19962	4.58E-06	16.46013	1.01E-05	23.7677
7.2E-07	9.314432	2.13E-06	12.28191	4.67E-06	16.59267	1.08E-05	24.11247
7.71E-07	9.349773	2.14E-06	12.35702	4.71E-06	16.72702	1.08E-05	24.27053
8.02E-07	9.447383	2.15E-06	12.44932	4.92E-06	16.88918	1.1E-05	24.56127
8.03E-07	9.483167	2.14E-06	12.56722	5.04E-06	16.97887	1.1E-05	24.84559
8.12E-07	9.575564	2.18E-06	12.6364	5.1E-06	17.14508	1.12E-05	25.11339
9.71E-07	9.605215	2.21E-06	12.75659	5.16E-06	17.27477	1.15E-05	25.45432
8.61E-07	9.694684	2.29E-06	12.7936	5.16E-06	17.43328	1.22E-05	25.6656
8.5E-07	9.74198	2.47E-06	12.91591	5.26E-06	17.57954	1.24E-05	25.94941
8.28E-07	9.830122	2.5E-06	12.95393	5.53E-06	17.75133		
8.88E-07	9.892893	2.5E-06	13.07845	5.64E-06	17.90203		
9.56E-07	9.956458	2.48E-06	13.14404	5.7E-06	18.0311		
1.02E-06	10.02044	2.5E-06	13.29791	5.84E-06	18.18603		
1.01E-06	10.11797	2.57E-06	13.33846	6.17E-06	18.36748		
1.01E-06	10.21865	2.69E-06	13.46814	6.32E-06	18.50279		

Table E-5: FCGR Test Results for Specimen STL614-34, R = 0.5 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
1.46E-06	7.336285	9.78E-07	10.13447	2.86E-06	13.88086	6.86E-06	20.14756
3.99E-07	7.403028	1.06E-06	10.25395	2.91E-06	13.99126	7.33E-06	20.36224
4.29E-07	7.445385	1.09E-06	10.30631	2.96E-06	14.10307	7.57E-06	20.52605
3.82E-07	7.512572	1.1E-06	10.33148	2.93E-06	14.18713	7.45E-06	20.74733
3.68E-07	7.554932	1.11E-06	10.46013	3.05E-06	14.27214	7.42E-06	20.9922
3.74E-07	7.628082	1.12E-06	10.50653	3.25E-06	14.42599	7.51E-06	21.1855
3.79E-07	7.663606	1.15E-06	10.58843	3.29E-06	14.54345	8.08E-06	21.41822
3.96E-07	7.764624	1.18E-06	10.64965	3.32E-06	14.63218	8.48E-06	21.6263
4.27E-07	7.833324	1.19E-06	10.71822	3.59E-06	14.77206	8.7E-06	21.75129
4.29E-07	7.881286	1.22E-06	10.80904	3.47E-06	14.87443	8.7E-06	22.01633
4.38E-07	7.923979	1.21E-06	10.85037	3.46E-06	15.02649	8.63E-06	22.22742
4.63E-07	7.988115	1.34E-06	10.94998	3.41E-06	15.17201	9E-06	22.5093
4.89E-07	8.018482	1.41E-06	10.98963	3.64E-06	15.23875	9.3E-06	22.70594
5.03E-07	8.095721	1.43E-06	11.10792	3.82E-06	15.39636	9.54E-06	22.96666
4.99E-07	8.149828	1.48E-06	11.1878	3.88E-06	15.51505	9.81E-06	23.16352
4.96E-07	8.23158	1.44E-06	11.25349	3.92E-06	15.64738	9.64E-06	23.48827
5.63E-07	8.280688	1.45E-06	11.34236	3.92E-06	15.76071	9.85E-06	23.66925
5.76E-07	8.335561	1.54E-06	11.43956	4.14E-06	15.88424	9.96E-06	23.94841
5.84E-07	8.401885	1.6E-06	11.49203	4.23E-06	16.05181	1.04E-05	24.16853
5.55E-07	8.451545	1.58E-06	11.58329	4.27E-06	16.13621	1.07E-05	24.4249
5.33E-07	8.605702	1.61E-06	11.64964	4.35E-06	16.3208	1.09E-05	24.68589
5.63E-07	8.667846	1.64E-06	11.76847	4.35E-06	16.44299	1.09E-05	25.0116
5.87E-07	8.695649	1.74E-06	11.79977	4.57E-06	16.57553	1.17E-05	25.24341
5.9E-07	8.787354	1.8E-06	11.8785	4.74E-06	16.70989	1.18E-05	25.48573
6.43E-07	8.838716	1.81E-06	11.98184	4.81E-06	16.8461	1.22E-05	25.83525
6.83E-07	8.878451	1.82E-06	12.06238	4.88E-06	16.99812	1.21E-05	26.11654
6.86E-07	8.948031	1.9E-06	12.18402	4.99E-06	17.12978	1.21E-05	26.40352
6.89E-07	9.006108	1.91E-06	12.25005	5.05E-06	17.29488	1.29E-05	26.7728
7.08E-07	9.070336	2.05E-06	12.3741	5.18E-06	17.41622	1.35E-05	27.00571
6.82E-07	9.120795	2.13E-06	12.41441	5.32E-06	17.56251	1.38E-05	27.27916
8.14E-07	9.193984	2.09E-06	12.51843	5.26E-06	17.75783	1.4E-05	27.69998
7.31E-07	9.271593	2.07E-06	12.6294	5.28E-06	17.87662	1.39E-05	28.01833
7.2E-07	9.325033	2.13E-06	12.70516	5.38E-06	18.06889	1.4E-05	28.30386
7.03E-07	9.40362	2.29E-06	12.7927	5.76E-06	18.22453	1.5E-05	28.64573
7.36E-07	9.468162	2.45E-06	12.91818	5.98E-06	18.4311	1.55E-05	28.988
7.66E-07	9.518573	2.44E-06	12.95619	6.05E-06	18.56728	1.57E-05	29.25898
7.87E-07	9.617923	2.39E-06	13.09016	6.09E-06	18.7466	1.59E-05	29.60393
8.42E-07	9.634775	2.44E-06	13.20836	6.16E-06	18.90389	1.6E-05	30.09016
9E-07	9.702915	2.51E-06	13.26589	6.24E-06	19.04681	1.63E-05	30.49589
8.72E-07	9.804179	2.69E-06	13.3771	6.76E-06	19.21731	1.75E-05	30.79361
8.68E-07	9.86675	2.65E-06	13.48125	6.88E-06	19.30909	1.82E-05	31.13881
8.64E-07	9.955622	2.58E-06	13.58668	6.71E-06	19.56625	1.82E-05	31.49105
8.65E-07	10.01916	2.69E-06	13.62925	6.76E-06	19.78899	1.92E-05	32.01949
9.05E-07	10.07664	2.77E-06	13.78169	6.78E-06	19.93632	1.86E-05	32.52458

Table E-6: FCGR Test Results for Specimen STL614-35, R = 0.5 Loading

da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)	da/dN Corrected (in./cycle)	ΔK Corrected (ksi√in.)
3.05E-07	7.419051	1.04E-06	10.31457	2.96E-06	14.16022	7.69E-06	20.65777
4.04E-07	7.54768	1.05E-06	10.38321	3.06E-06	14.28176	7.82E-06	20.84902
3.68E-07	7.593838	1.08E-06	10.4615	3.14E-06	14.37759	7.81E-06	21.10194
3.53E-07	7.663629	1.11E-06	10.51509	3.19E-06	14.4746	8E-06	21.27548
3.41E-07	7.701479	1.2E-06	10.58522	3.4E-06	14.60037	8.03E-06	21.47994
3.53E-07	7.770058	1.23E-06	10.63955	3.46E-06	14.66666	8.03E-06	21.68778
4.1E-07	7.823302	1.27E-06	10.73413	3.43E-06	14.79837	8.1E-06	21.83688
4.55E-07	7.88714	1.27E-06	10.82709	3.44E-06	14.93963	8.73E-06	22.05592
4.62E-07	7.930311	1.26E-06	10.86139	3.51E-06	15.06312	9.14E-06	22.27379
4.64E-07	7.977142	1.44E-06	10.95331	3.6E-06	15.15694	9.25E-06	22.51997
4.55E-07	8.059513	1.36E-06	11.04611	3.69E-06	15.29197	9.29E-06	22.80318
4.83E-07	8.124498	1.35E-06	11.11556	3.76E-06	15.36817	9.26E-06	22.96091
5.2E-07	8.157448	1.32E-06	11.17577	3.81E-06	15.52662	9.28E-06	23.25555
5.21E-07	8.222908	1.33E-06	11.24127	3.91E-06	15.58126	9.45E-06	23.46812
5.17E-07	8.283284	1.39E-06	11.3346	3.9E-06	15.76386	9.99E-06	23.70511
5.09E-07	8.332896	1.48E-06	11.4114	3.99E-06	15.88998	1.03E-05	23.92002
5.28E-07	8.388179	1.54E-06	11.47125	4.28E-06	16.03525	1.05E-05	24.20227
6.63E-07	8.443689	1.65E-06	11.59233	4.46E-06	16.14018	1.06E-05	24.52082
5.57E-07	8.544412	1.69E-06	11.63819	4.62E-06	16.26776	1.06E-05	24.7373
5.64E-07	8.60633	1.74E-06	11.71512	4.57E-06	16.41007	1.07E-05	25.07371
5.43E-07	8.657138	1.73E-06	11.78244	4.55E-06	16.55448	1.16E-05	25.31118
5.72E-07	8.736856	1.7E-06	11.88679	4.71E-06	16.66577	1.2E-05	25.51366
6.19E-07	8.799746	1.77E-06	11.98169	4.79E-06	16.80056	1.21E-05	25.83292
7.74E-07	8.886258	1.82E-06	12.04323	4.84E-06	16.93721	1.19E-05	26.14125
6.94E-07	8.920713	1.85E-06	12.14245	4.9E-06	17.13456	1.19E-05	26.46752
6.69E-07	8.955144	1.88E-06	12.21611	4.88E-06	17.24454	1.21E-05	26.68838
6.09E-07	9.048568	1.94E-06	12.30665	5E-06	17.38738	1.33E-05	26.99032
5.98E-07	9.14869	2.04E-06	12.42235	5.13E-06	17.57826	1.38E-05	27.29803
6.7E-07	9.238037	2.07E-06	12.45462	5.5E-06	17.72557	1.39E-05	27.64809
7.62E-07	9.273352	2.07E-06	12.54201	5.75E-06	17.85159	1.38E-05	28.00057
7.37E-07	9.308676	2.18E-06	12.64414	5.81E-06	17.95578	1.37E-05	28.32326
7.49E-07	9.387079	2.27E-06	12.7808	5.87E-06	18.12043	1.4E-05	28.58127
7.52E-07	9.480581	2.3E-06	12.83482	5.99E-06	18.31977	1.53E-05	29.0354
7.65E-07	9.527002	2.33E-06	12.93207	5.87E-06	18.47815	1.6E-05	29.26673
8.29E-07	9.600894	2.35E-06	13.04754	5.91E-06	18.65926	1.61E-05	29.65897
8.54E-07	9.662627	2.4E-06	13.11797	6.13E-06	18.82669	1.6E-05	30.05612
8.62E-07	9.724729	3.06E-06	13.21219	6.25E-06	19.01738	1.6E-05	30.42192
8.58E-07	9.767767	2.64E-06	13.30161	6.41E-06	19.11058	1.61E-05	30.71702
8.66E-07	9.836802	2.57E-06	13.38026	6.52E-06	19.34469	1.73E-05	31.14164
8.78E-07	9.902148	2.38E-06	13.51117	6.52E-06	19.48898	1.83E-05	31.44996
9.05E-07	9.963554	2.54E-06	13.62599	6.65E-06	19.66524	1.86E-05	31.84195
9.83E-07	10.04294	2.74E-06	13.74084	6.75E-06	19.87031	1.88E-05	32.25478
1.02E-06	10.13401	2.92E-06	13.83587	7.18E-06	20.10499	1.69E-05	32.66987
1.03E-06	10.18353	2.87E-06	13.92976	7.5E-06	20.28596	1.75E-05	33.18378
1.04E-06	10.25555	2.98E-06	14.04012	7.65E-06	20.44745		

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